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GENERAL MOTORS CORPORATION

ROVING VEHICLE MOTION CONTROL

~~FIRST~~ QUARTERLY REPORT
COVERING THE PERIOD
1 MARCH 1967 THROUGH 31 MAY 1967

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ABSTRACT

This report covers the first three months effort on a Roving Vehicle Motion Control Study conducted by AC Electronics - Defense Research Laboratories under a contract with the Jet Propulsion Laboratory. The objectives of the study are outlined, and the general approach is briefly discussed. The nature of the problem of remote control of extraterrestial roving vehicles is developed in terms of discrete increases in the level of difficulty associated with increasing orders of magnitude of the distance between the roving vehicle and the control center.

Several prior studies are reviewed to extract conclusions relevant to the present study. The basic astrodynamic and astrophysical constraints operative in the lunar and planetary cases are defined and the basic parameters of the Deep Space Network that pertain to remote control of roving vehicles are outlined.

A rationale is described for the generic characterization of roving vehicle missions in terms of basic functions, modes of operation, navigation requirements, and the means by which these are characterized. In addition, three distinctly different terrain models are postulated. The formalization of system requirements from these mission characteristics and terrain models is demonstrated by carrying an example through successive levels of detail to arrive at a level suitable for the assignment of hardware and software functions and the preliminary configuration of systems.

Finally, the present and projected state of the art in the applicable hardware subsystem technologies is reviewed in order to establish a basis for subsequent system mechanization and parametric tradeoff analysis.

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1. INTRODUCTION

1.1 OBJECTIVES OF THE STUDY

As the U.S. Space Program progresses toward the first manned landings on the moon, it is important to consider the directions in which subsequent exploration should head and the associated problems and requirements. Among the diverse possibilities are included extended-area unmanned exploration of the moon and unmanned landings on the planet Mars. In both cases, cogent reasons can be given for including the capability to move about, i.e., for the incorporation of a roving vehicle on the landing spacecraft. The feasibility of doing so, however, hinges directly upon the ability to control the movements of the vehicle in a safe and effective manner from the earth. To investigate this problem, the Jet Propulsion Laboratory has initiated a study of methods and techniques that might be used to achieve this control capability.

This is the first quarterly report on Phase I of the Roving Vehicle Motion Control (RVMC) study conducted by AC Electronics - Defense Research Laboratories under contract No. 951829 with JPL. The objective of the study is to analyze the various possible system configurations and techniques applicable to the control of unmanned roving vehicles on the surfaces of the moon and planets. Within this objective the study is to define the relative significance of system parameters and the effect of constraints imposed by distance, weight, environment, and communication limitations. Particular attention is to be paid to the role of the human in the operational control of unmanned roving vehicles and the methods of selecting, training, and using human operators.

Out of the study are to come recommendations for systems and procedures which show promise of meeting the needs of roving vehicle control and an evaluation of their relative capabilities under a variety of operational conditions. It is also desired that the critical technological areas be identified and that appropriate experimental effort be described for verifying the premises of the study and testing the resulting concepts.

1.2 GENERAL APPROACH

The remote control of vehicle motion at lunar and planetary distances involves a complex, intimate interplay of several elements:

- Environment (especially terrain)

- Roving vehicle mission
- Vehicle (locomotion subsystem)
- Sensors, and associated remote data storage and processing
- Telecommunications, including relay links and the DSIF/GCS (Deep Space Instrumentation Facility/Ground Communication System)
- Operational support equipment, including SFOF (Space Flight Operations Facility)
- Operator(s) and procedures

In synthesizing control systems to perform given missions all of these elements must be carefully taken into account, and they must be optimized as an integrated system. Accordingly, the problem is one of system design, wherein the performance parameters of the overall system are optimized with respect to chosen criteria subject to certain constraints, and where none of the above elements is considered independently of the others.

This is the approach which is being followed. The first steps in the study have been to review prior work in the field of roving vehicle remote control and to define the basic constraints which are germane to the problem. There has been, of course, no directly applicable experience, and the prior analytical and experimental work that has been done was directed mainly at lunar applications. This work is briefly reviewed below.

The most significant environmental factor influencing the control of the roving surface vehicles is the character of the terrain. Three terrain models were postulated, each of which offered a significantly different control problem, so that the effects of the terrain upon the control system and techniques could be studied. Likewise, a generic set of mission characteristics was defined in such a manner as to cover a broad range of system requirements.

From these terrain and mission characteristics evolve the requirements which control systems must meet to perform a useful role in extended lunar and planetary exploration. The task of delineating these requirements has now been formalized, and this was the concluding effort of the first quarter.

Concurrent with the above foundational work, a survey has been conducted, and is continuing, to define the state of the art and the promising trends in each of the hardware subsystem technologies involved — sensors, displays, power, communication, mobility, and data handling. This provides a "data bank" upon which to draw in synthesizing candidate systems to meet the system requirements evolved above.

Work through the first quarter has thus laid a foundation for the configuration of candidate systems and their comparative evaluation, which will in turn lead to recommended systems and techniques suitable for more detailed consideration. The remainder of the study will be devoted to this task. A number of alternative systems will be configured to meet the above requirements. The parameters of each candidate system will be traded off within the basic constraints to achieve a first-order optimization. Meanwhile a functional flow analysis will be conducted for each system showing functional interfaces and identifying the functional breakdown between man and equipment, and criteria will be established for the comparative evaluation of the system configurations. Finally, the systems will be compared and the relative advantages and disadvantages of each will be identified and evaluated.

The flow of work for the entire study is shown in Figure 1-1.

1.3 JPL GROUND RULES

During the first quarter, as the above work proceeded, certain guidelines were established by JPL. These guidelines provided a basis for placing emphasis in particular preferred directions. These are ennumerated as follows:

(1) Consider that the mission is basically to move out of the contaminated landing area, the minimum radius of interest being 2,000 feet. Vehicles should not be range-limited and ranges of hundreds of miles may be of interest on later missions.

(2) Energy reserve is needed on vehicles to do useful work in addition to locomotion requirements.

(3) Planetary considerations should be limited to Mars for the present.

(4) No immediate attention should be given to missions on the lunar far side nor in the higher latitudes of Mars.

(5) Vehicle gross weights in the range of 750—900 pounds are of primary interest for both lunar and planetary cases. This range will then be the pivot about which parametric variations will be studied.

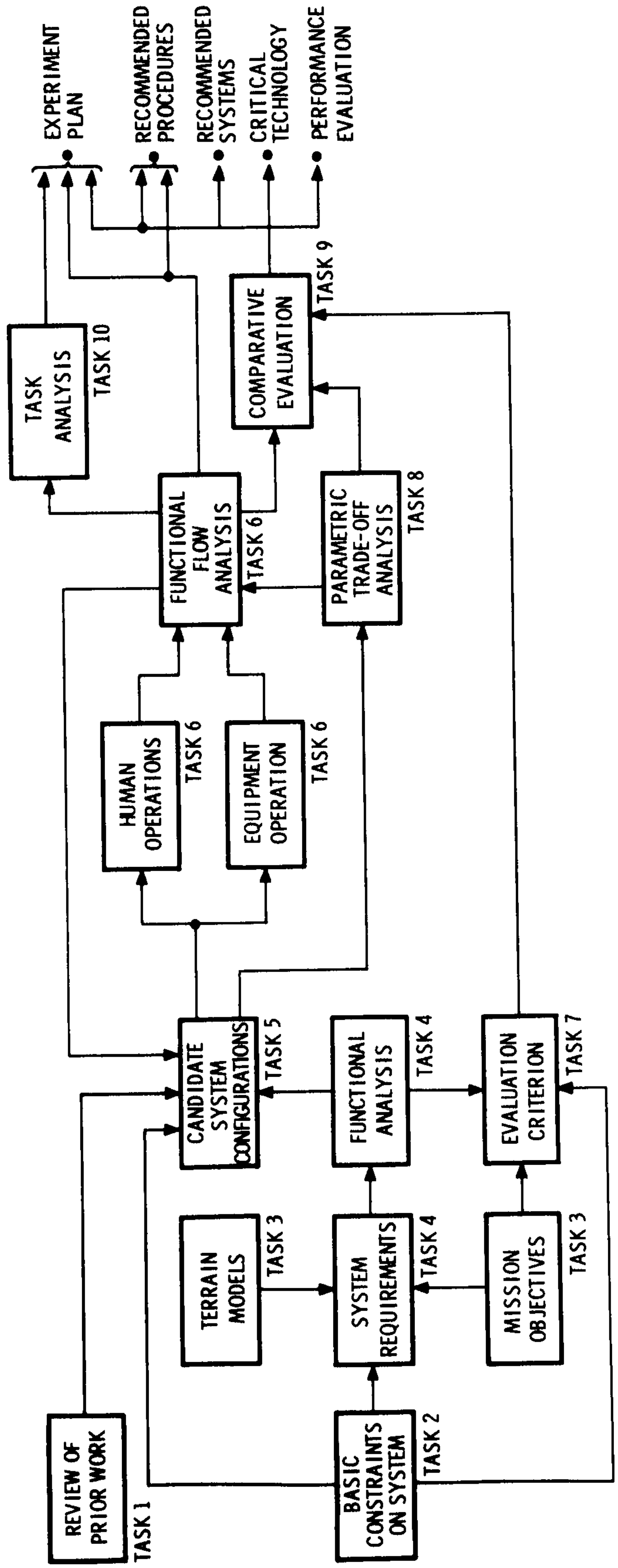

Figure 1-1 Study Flow Diagram

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2. THE NATURE OF THE ROVING VEHICLE CONTROL PROBLEM

2.1 EFFECT OF CONTROL DISTANCE

The complexity and difficulty of controlling a vehicle are directly dependent upon the distance between the vehicle and the controller. In fact, several distinct levels of difficulty may be associated with orders of magnitude of this distance. These levels of difficulty are tabulated in summary form as technical problems in Table 2-I.

Table 2-I
INCREASING CONTROL COMPLEXITY WITH DISTANCE

	Approximate Distance to Vehicle	Problems
On Earth	Alongside to approx. 40 meters	Vehicle mobility performance Command and actuation precision
On Earth	Approx. 40 meters to 40 km	The above plus: Imaging sensor performance Transmission of sensor data Information display
On Earth	Approx. 40 km to 40,000 km	The above plus: Power, bandwidth, information rate tradeoffs Relay links
Lunar	400, 000 km	The above plus: Transmission lags (seconds) Earth rotation Unknown environment Payload restrictions Spreading losses
Planetary	40×10^6 to 400×10^6 km	The above plus: Transmission lags (minutes) Relative motion of earth and planet Greater spreading losses

2.1.1 Operator Alongside Vehicle

An operator walking alongside the controlled vehicle can decide, by direct observation, upon a path leading to the safe achievement of a desired objective. The major control problem is that of incorporating sufficient performance in the vehicle to enable the desired motion to be accomplished. This implies adequate vehicle mobility, fineness of control actions, and predictability of results of control actions. The sensory capability is that of the operator directly. Command channel requirements are minimal; it is only necessary that an experienced operator have available a means of communicating the appropriate locomotion commands to cause the vehicle to move along the desired path. This can be accomplished using control buttons or levers on the vehicle itself, by a mechanical cable connection (as with tethered model aircraft), with electrical cables connected between the vehicle and a control box, or with a relatively simple radio link. None of these approaches presents any great difficulty and, in fact, all have been used with considerable success.

2.1.2 Distances to a Few Kilometers

If the vehicle is moved, say, a few kilometers from the controller, a new problem arises: the need to sense the immediate environment of the vehicle, and by some means to transmit these data to the controller so that he may make valid control decisions. The problem of transmitting sensor data introduces a new level of difficulty. A sensor of some sort is needed on the vehicle. Its performance is probably inferior to that of direct human observation in resolution, depth perception, color discrimination, and other factors. A means for transmitting the images, e.g., radio, is required and this data link contributes noise, distortion, and bandwidth limiting to the information delivered to the operator. The operator's display device has limited fidelity and light intensity far below that of the original scene. Thus the perception and evaluation capability of the operator is much reduced by the sensor-radio-display chain. In contrast, the command channel and control actuator aspects are not seriously affected. Remote control at these distances is generally possible using continuous, real-time visual imaging. Although this approach may be costly in terms of power or bandwidth, these resources are usually not at a premium and pictures of adequate quality can usually be transmitted at a sufficient frame rate to make this approach feasible.

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2.1.3 Distances of Hundreds of Kilometers

As the distance between the vehicle and the controller is increased still further to, say, hundreds or thousands of kilometers, one is increasingly concerned about power and bandwidth considerations in the sensor-radio-display chain. Tradeoffs between frame rate, resolution, and field of view on the one hand, and power and bandwidth on the other, may have to be examined carefully. Another new factor shows up at these ranges, since the operator and vehicle may be beyond line-of-sight to each other. In this case, the design must consider the alternatives of either 1) wire circuits or low-radio-frequency operation, with their problems of bandwidth restriction and interference, or 2) the use of communication relay procedures. The latter may take the form of land-based receiver-transmitter stations, or, if the distances involved become substantial, orbital relays may be suitable.

2.1.4 Lunar Distances

Extending to lunar distances, all of the problems heretofore noted become more difficult. The information rate, power, and bandwidth tradeoffs become vastly more critical. They are much more closely related to the vehicle itself and to the often limited power and energy available because of booster and spacecraft payload limitations. On the moon, the generally hostile and largely unknown environment makes accurate control more critical. The increase in distance of one or two orders of magnitude causes severe communication losses due to spreading. At these distances, a new factor, communication time lag, becomes appreciable, and control philosophy must take it into account. A consistent conclusion of various lunar-vehicle remote-control studies has been the demonstrated need for "predictive" display aids to stabilize the operator control function. Motions of the earth and moon cause the communication path to vary both in elevation angle at an earth receiver and in length, causing doppler effects. Rotation of the earth also restricts the operating window from any single DSIF site on earth, such as Goldstone, to about 8—10 hours per earth day.

2.1.5 Planetary Distances

Operation on the surface of planets involves all of the above problems, with each one being more severe. The most pronounced effects are directly related to the increase in distance of two to three orders of magnitude, compared with lunar operations. Communication lags are measured in minutes rather than seconds, and spreading losses are much greater. While the distances involved in interplanetary control make antenna directivity more important, the more complex motions of planets make it more difficult to achieve, and these motions also make operating windows restrictive.

In summary, the difficulty of the control problem is seen to expand hierarchically with distance. This difficulty increases in discrete steps through the introduction of new problems at greater distances. As was shown previously in Table 2-I, all problems existing at lesser distances carry over and become more critical and more severe. This tendency, in turn, forces an increasing interdependency of the elements of any remote vehicle control system, such that, at planetary distances, the parameters of any one element cannot be meaningfully determined without relating that element to all of the other elements in a tightly knit system approach.

2.2 ELEMENTS OF THE CONTROL PROBLEM

Control itself consists of three basic actions — observation, decision, and command, as shown in Figure 2-1. Observation involves sensing the immediate surroundings of the

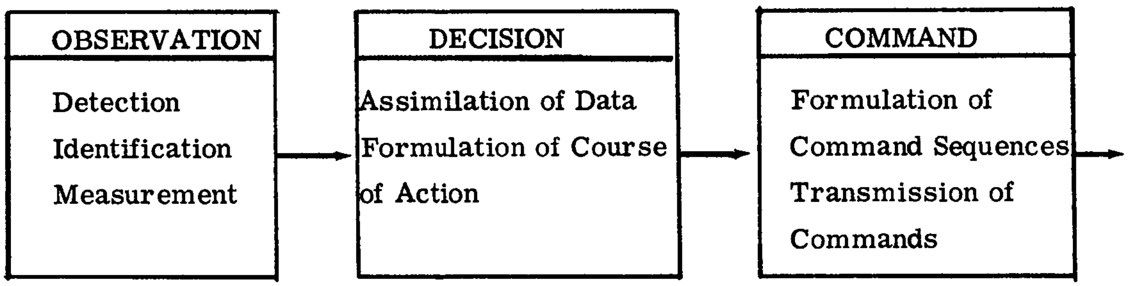

Figure 2-1 Elements of Vehicle Control

vehicle by visual or other techniques, and consists of the detection, identification, and measurement of mobility hazards out to a range at least as great as the travel distance of the vehicle between the next command and the one following that. It should be noted here that vehicle mobility can be traded off against detection and measurement accuracy in the sense that as the obstacle size that the vehicle can safely negotiate is increased, the importance to safety of measurement accuracy on smaller obstacles is lessened.

The decision process involves the assimilation of all of the above data and, in the context of some desired locomotion objective, the formulation of a course designed to move the roving vehicle safely and efficiently toward the objective. The decision process may be supported by such information storage, display, and simulation capabilities as are necessary to provide the operator with available information of his choosing, and which may enable him to pretest the effects of commands prior to their actual transmission.

The final action in the control process consists of the formulation and transmission of a specific start, stop, or steer command or a sequence of such commands, or a destination command, which will cause the vehicle to move along the desired course.

Of the three elements above, observation and decision-making are the most complex and the most critical. The successful attainment of mission objectives is crucially dependent upon accurate perception and avoidance of hazardous situations. The efficiency and efficacy of the decision and command functions are contingent upon both the quantity and the quality of sensor data available. In turn, the requirements for sensory data and the number of commands can be reduced by proper information storage, processing, and retrieval in the ground support complex.

Herein lies the crux of the control problem — how to obtain and assimilate sensor data in sufficient quantity and quality to maximize the payoff in terms of specific mission objectives. This involves tradeoffs among all elements of the system and involves both the mission itself and the nature of the terrain.

3. PRIOR RELATED STUDIES

Five previous studies related to remote vehicle control have been reviewed. Within the five studies, which were conducted by several organizations, there is some degree of overlap. In addition, there are factors related to remote vehicle control which are not covered by any of the studies. It was the purpose of this review to determine which findings are useful in the present study program and which areas need further study and experiment. Conclusions from each of the studies are briefly summarized and the results are correlated where possible.

3.1 "SLRV CONTROL STUDY," AC Electronics - Defense Research Laboratories (Final Report, AC-DRL Report No. TR65-20, March 1965, JPL Contract No. 951056)

This study consisted of two phases. First, potential operators participated in perception tests in the laboratory, using stereo television displays. Second, a remotely controlled vehicle (Modified Engineering Test Model of SLRV) was operated on an outdoor "Lunarium" by operators in an indoor control room. Operators were presented with either monoscopic or stereo television displays of views from the vehicle. These tests yielded the following conclusions.

3.1.1 Perception Tests

- When stereo displays are required, operators must have adequate depth perception. Properly selected operators have no difficulty in viewing and measuring objects in a television stereo model when vertical and horizontal alignment and scale are carefully controlled.
- Accuracy of stereo measurement increases with length of baseline for objects at a given distance. However, for fusion of the stereo pair, the ratio of the distance from the nearest subject to the length of the baseline should seldom be less than 10/1 and, for comfortable viewing, should be even greater. System design should also provide adequate stereo overlap.
- The television system used for the perception tests permitted the use of different values for parameters such as camera height, length of baseline, resolution, and signal-to-noise ratio. The most important source of measurement error turned

out to be television geometrical nonlinearities. Figure 3-1 shows curves of total error and operator readout error for 5-inch and 9-inch baselines. Errors are maximum errors since, for vehicle control, standard deviations are not suitable. Thus the distance to a crevice edge 7-1/2 feet from the camera can be measured, with a 9-inch baseline, to ±5 inches, with ±2 inches attributed to operator readout error. A typical slope measurement total error was ±4 degrees at 9 feet from the camera. The commercial television system used in the tests had 5-1/2% geometrical linearity. State-of-the-art systems can provide better than 1%, which will considerably reduce the total measurement errors.

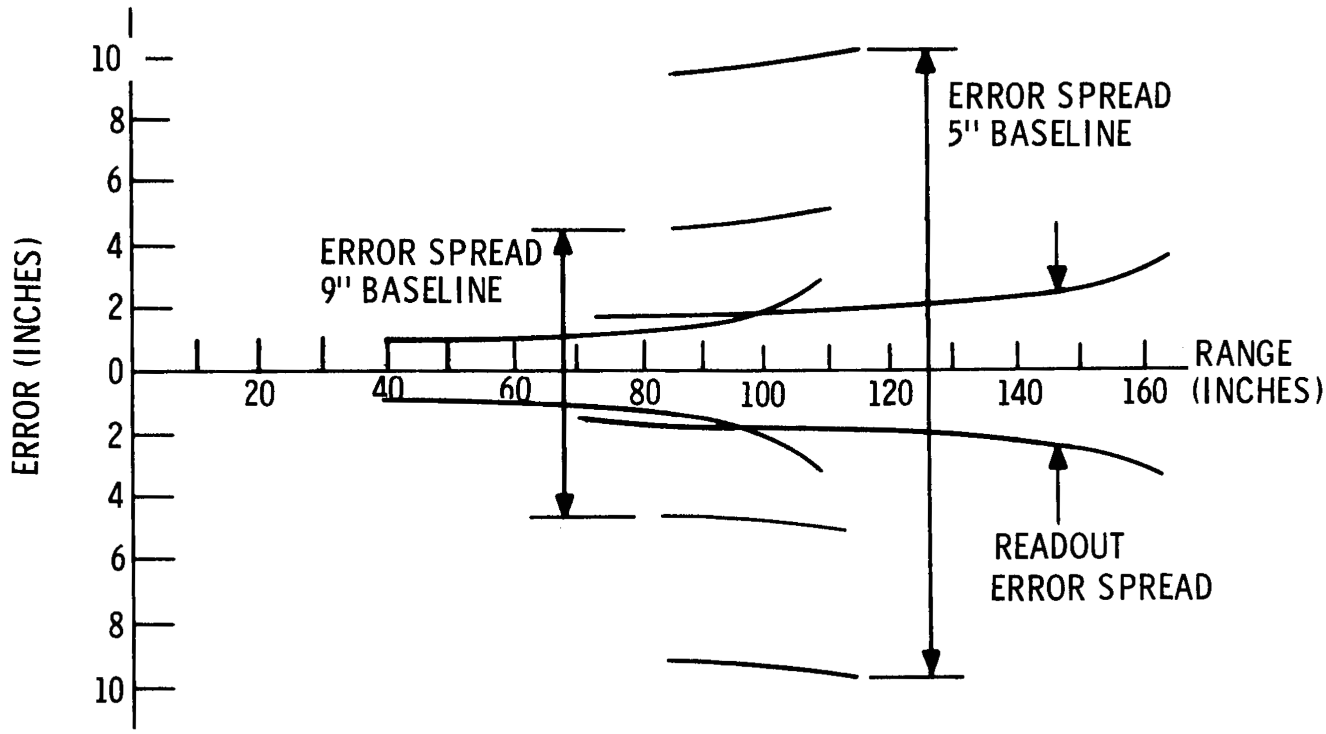

Figure 3-1 Range Error in Estimating Points

3.1.2 Control Tests

- The 525-scan-line television system used in the study proved more than adequate for maneuvering the vehicle through the test course. Systems with as few as 200 or 300 lines might be adequate for vehicle control.
- A camera height of 35 inches with a 15° down angle provided a suitable view of the terrain for the remote operator. However, a greater camera height would be desirable for viewing further away than two wheel revolutions (about 10 feet). A

45° horizontal field angle appears to be adequate. Twenty-four degrees was only suitable for steering straight ahead.

- A step-motion distance of 1/2-wheel revolution (about 30 inches) appeared to be proper for maintaining control of the SLRV in the large majority of cases. A 1/4-wheel revolution step capability would help for tight maneuvering. Continuous wheel motion could be used over smooth terrain.

- The resultant error rates and command rates indicated that the SLRV could be maneuvered on the moon with monoscopic or stereoscopic TV with approximately equal proficiency provided that:

  1) The area being traversed has been previously certified as negotiable with respect to vehicle mobility.
  2) Some form of stereo presentation is available when accurate measurements are to be made.
  3) The operator is highly proficient in photo interpretation and vehicle attitude information is available.

- Perception aids significantly improved steering and maneuvering accuracies. A means of selecting and viewing previously taken TV pictures would be of significant assistance to the vehicle controller.

- A transmission time of 1.25 seconds was added for each driver command and picture return. This time delay is not detrimental for vehicle control provided step motion is used, although it does result in a slight reduction in average vehicle speed.

- In comparing errors using the monoscopic and stereoscopic configurations, there were only small differences in error rates. The minor error rates were almost identical while the stereoscopic configuration showed slightly better performance with respect to major errors in spite of the narrower field of view. The primary advantage of the stereo system was the depth relationship between the vehicle tires and the roadway that was shown in the TV image for roadway tests. Also, crevices and other obstacles were detectable and measurable where a monoscopic image was meaningless in certain cases.

3.2 "SURVEYOR LUNAR ROVING VEHICLE INTERIM STUDY," Bendix Systems Division (Final Report, February 1965, JPL Contract No. 951057, BSR 1096)

This study consisted of two phases. First, a Developmental Test Program was carried out to determine the influence of various viewing parameters on surface assessment.

Second, a remotely controlled vehicle (modified ETM), was operated in a simulated environment and mission conditions. The conclusions were:

- Generally, control failures did not result from inability to recognize gross hazards such as excessive slopes, undercarriage clearance, or other obstacles approaching the vehicle's calibrated mobility values. Rather, failures resulted from hazards which caused one or more traction units to stall (such as wedging between two rocks each of which was well within the obstacle crossing capability of the vehicle). Changing the vehicle's path an inch would frequently remove the hazard. Such features indicate areas where greatest mobility design emphasis should be placed.

- Numerical safety factors can be assigned but cannot be applied to very rough areas of a random test course. The vehicle's performance must be measured against the spatial relationship of many features and obstacles.

- Remote control of a vehicle over random terrain approaching and sometimes exceeding the mobility capability of the SLRV is not feasible as a normal means of operation, but rather only to traverse locally rough areas.

- The remote control of an SLRV requires control aids in addition to a basic stereo display and vehicle attitude sensor when operating in rough terrain. These aids may be in the form of mechanical safety devices or optical measurement improvement devices such as photogrammetric ranging aids.

- The operation of the ETM on a test course approaching, and in certain areas exceeding, vehicle mobility, although tedious, resulted in a few catastrophic failures. The conclusion is drawn that if the lunar terrain is less rough than the test course there will be a high confidence in mission success.

- Quantitative measurement indicated only a slight advantage for stereo display; the advantage was more apparent on rough terrain. Throughout the test program the operators thought that stereo was desirable for terrain assessment and that they could better interpret the geometry of the overall scene with a stereo display. An interocular stereo baseline was preferred for ease of viewing. Where accurate objective measurements of surface geometry are required, this baseline is inadequate.

- The dispersion in size-and-distance judgements through either a stereo or monocular display was approximately three times greater than that with direct viewing. This indicates considerable room for improvement through more effective image display, training, and experience.

- An optical sensor with a field of view of 70° or greater is recommended. Generally it is not necessary to show the extremities of the vehicle in the display, if their position with respect to scene geometry is known to the operator. Of the several optical sensor positions used during the program, a lower height located back from the front of the vehicle was preferred by the operators. Thus, the optimum optical sensor location may not be the highest position above the terrain, as was anticipated.
- Frequently, operators requested multiple TV pictures before completing terrain assessment. A mosaic display presentation and/or rapid video data retrieval is recommended. The grey-level rendition and resolution of a vidicon was satisfactory.
- An odometer and heading and steering angle sensors are required on the vehicle. These sensors make possible closed-loop driving where step distance and/or direction changes are made without stopping the vehicle to take a new sequence of pictures. The advantage of closed-loop driving and a path prediction aid was apparent during computer-generated electronic display simulation testing.
- Unless the vehicle is equipped with a sensor that can see into shadows, or unless the vehicle is equipped with a headlight, it will be virtually impossible to assess the characteristics of a surface within a shadow area.

3.3 "AN INVESTIGATION OF THE EFFECTS OF THE TIME LAG DUE TO LONG TRANSMISSION DISTANCES UPON REMOTE CONTROL," J. L. Adams, Stanford University (Final Report, November 1961, NASA Contract NSG 111-61)

This study consisted of two experimental phases and a third phase to correlate results. First, tracking experiments were made where operators attempted to cause one vertical line (vehicle) to follow a randomly moving vertical line (roadway) on an oscilloscope. Second, a remotely controlled vehicle was built and tested on three different courses marked on a parking lot.

Tracking experiment conclusions were:

- Tracking error was always greater when the operator tried to keep the lines in coincidence than when he moved his control knob to follow the randomly moving line.
- Tracking error was always greater with acceleration control than with velocity control.
- Tracking error always increased with delay time.
- Tracking error always increased with target speed.

Vehicle experiment conclusions were:

- Vehicle tracking error increased with delay time and vehicle speed. The error curves approximated those for similar tracking experiments.
- Because of continuous motion, a vehicle tracking error became compounded since there was no opportunity to stop, collect further information, and correct the error.
- The limited and fixed field of view led to major mistakes when the course was not visible.
- When obstacle spacing or changes in course were equal to the product of speed and delay time, avoidance of collisions with marked obstacles was not possible. Thus, at full speed, for the given conditions the vehicle became uncontrollable with more than two seconds time delay.

3.4 "A SIMULATION STUDY OF OPERATOR CAPABILITY IN ROBOT VEHICLE CONTROL," M. Chomet, N. Freeberg, and A. Swanson, Airborne Instruments Laboratory, (Presented at IRE International Convention, March 1962)

A closed-circuit television camera was mounted on a vehicle simulator with electric steering and propulsion remotely controlled. Each operator guided the vehicle along each of three video-presented courses with 2, 3 and 4 turns respectively. Each course appeared as a white line on the screen with no other visual cues. A forward 55^{o} wide-angle view and an overhead 360^{o} circumferential view (using a reflecting sphere) were evaluated. All test runs were made with a 3-second delay between control input and vehicle response.

The conclusions were:

- The authors refer to earlier work showing that, "when driving between numerous obstacles, operators can become geographically disoriented with a simple video display and a 3-second control delay. In addition, anticipatory control inputs are limited to about 3 for experienced operators so that control impulses generally deteriorate to repeated stop and start driving." In this study each straight leg prior to a turn would appear to have required 12 seconds or more to traverse. Thus, conditions for disorientation were not present.
- Mean deviations from the path were greater, on all three courses, for the panoramic view than for the forward view. This was attributed to deviations from the path appearing smaller on the compressed view as compared to the direct view.

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- Mean number of stops and mean time to complete the course were greater, on all three courses, for the forward view than the panoramic view.
- For all performance measures, there was poorer performance with increased course complexity.

3.5 "A STUDY ON THE CONCEPTUAL DESIGN OF A REMOTE CONTROL STATION," Serendipity Associates, (Final Report, Sept, 1964, JPL Contract No. 951313, TR-34-66-31(U)

The objectives of the Serendipity study were (1) to develop a systems analysis technique which could be used to evolve a design concept for a remote control station for spacecraft, in conjunction with the Deep Space Network, and (2) to use the method to create a design concept for control of a generic spacecraft of the type likely to be available from the present time until 1973.

A formal approach to systems engineering is described in this study, involving (1) a basic set of engineering assumptions,(2) a set of systems-design concepts, and (3) a set of ground rules for applying the concepts to the design problem. By successive applications of synthesis and analysis a data-proliferation methodology stemming from overall system requirements is carried through various levels to arrive at a design concept.

The resulting concept is expressed as a block schematic in terms of function flow, data processing and display, and interface requirements with the SFOF/Deep Space Network (DSN). Lack of specific values for system parameters, and of definite knowledge of mission characteristics resulted in the Serendipity design concept being quite general. Nevertheless, the formalization of system design methodology is an aspect of system engineering that has long been overlooked by designers. Analyzing the requirements for control of a roving vehicle necessarily carries system specifications to successively lower levels than that achieved by Serendipity, but much of their methodology bears directly upon the present problem.

3.6 CORRELATION OF STUDY CONCLUSIONS

The remotely controlled vehicle studies by Chomet, et al, and Adams, just discussed, dealt with control of continuously moving vehicles. Continuous television displays were used in the presence of time delays up to three seconds between transmission of a command and receipt of a picture. Both studies show that continuous control is possible when obstacle spacing or distance between changes in course is greater than time delay times speed. Where distances are less, the problem of disorientation is greatly reduced by using stop-start driving. It is also alleviated by using predictive displays where the operator, in effect, drives a vehicle when viewing as if from a predicted position.

The studies by AC-DRL and Bendix Systems Division dealt with stop-start driving and transmission of intermittent pictures. Vehicle motion was halted to transmit, record, and evaluate video information before sending commands for further motion. Both of these studies also demonstrated the value of predictive aids.

All four of the above studies assumed primary dependence on pictorial displays for operator control. This points out the lack of experimental studies using synthetically generated displays and of using nonimaging sensors, either exclusively or to supplement video information.

All four studies show that a vehicle can be remotely controlled using monoscopic images and assuming relatively non-hazardous terrain. There is general agreement between studies by AC-DRL and Bendix Systems Divisions that stereo capability is often desirable and sometimes necessary. This need is established by surface geometry and mission requirements. Therefore no general rule can be established concerning the need for stereo.

The experiments by Chomet et al at A.I.L. showed improved performance, by photographing a reflecting sphere on the vehicle, except for path deviations. An improved optical system might even reduce path deviations. This, in effect, gives a plot-plan display of vehicle/terrain relationships. Although similar displays are often discussed in connection with remote vehicle control, this seems to be the only experimental work reported.

Considering the promising experimental results, the development of optics such as Marquardt Corporation's 360° optical system, and the need for a less restricted field of view, further experimental study is desirable.

4. STUDY FOUNDATIONS

4.1 BASIC CONSTRAINTS

In any system problem, one generally faces certain basic constraints which are inviolate. In this study, the most obvious of these are imposed by the astrodynamical and astrophysical situations — communication distances, relative movements of the earth and survey bodies (moon and planets), and the levels of illumination, surface properties, and other physical properties of the survey environment and the intermediate propagation path.

In addition, certain other constraints are assumed to apply in order to provide reasonable and realistic bounds on system costs and time frame. These constraints presume that system masses and form factors must be consistent with existing or planned launch vehicles and spacecraft.

Major changes in the Deep Space Instrumentation Facility, the Ground Communications System, or the Space Flight Operations Facility of the Deep Space Network, are assumed to be limited to those currently planned. If the study uncovers changes in the DSN that would be highly desirable from the standpoint of vehicle motion control, they will be fully reported.

4.1.1 Astrodynamic Constraints

Within the framework of rocket and space vehicle technology and the Deep Space Network characteristics, the particular concerns of this study are the bounds placed upon roving vehicle weight, controllability, and information transferral capability imposed by the astrodynamic constraints. For any interplanetary mission, several interdependent variables must be traded off to arrive at an overall system design. The most significant of these are the following:

1) Launch vehicle capability.
2) Departure trajectory asymptote maximum declination.
3) Maximum and minimum launch azimuth.
4) Launch date.
5) Arrival date.

6) Communication distance at and after arrival.
7) Heliocentric angle between earth and the target planet at and after arrival.
8) Launch period.
9) Daily launch window.
10) Parking orbit altitudes.
11) Landed payload mass.

The resulting variables of interest in this study are:

1) Gross weight of the landed roving vehicle.
2) Communication distances at arrival and thereafter.
3) Sun-Mars-Earth angle (cone angle) at encounter and thereafter.
4) Latitude and right ascension of the sub-earth point referred to a Martian coordinate system.

4.1.1.1 ROVING VEHICLE WEIGHT. As of the writing of this report, only a few sources are available which give substantial data regarding realistic landed payload possibilities. Of these, the most applicable is Reference 1, in which Mars opportunities from 1973 to 1984 are analyzed for a Saturn V launch vehicle and certain contingency factors. The analysis was conducted for a variety of constraints on launch asymptote declination, launch periods, arrival dates and Martian orbit apsidal distances. Resultant weight estimate breakdowns for "standard" Voyager flight capsules are shown in Table 4-I. These estimates are based upon two planetary vehicles per launch vehicle.

Table 4-I
STANDARD FLIGHT CAPSULE WEIGHT BREAKDOWNS

	First Generation (lb)	Intermediate (lb)	Advanced (lb)
Landed Science	400	660	1,070
Landed Science Support	1,070	1,070	1,070
Sub-Total	1,470	1,730	2,140
Entry Payload	45	45	45
Capsule Bus Inert Wgt.	2,265	2,240	2,260
Heat Shield	1,050	1,050	1,050
Terminal Propellant	820	900	1,090
De-Orbit Propellant	550	580	640
Canister	785	785	785
Total	6,985	7,330	8,000

The science payload and support could be considered to be partly or wholly devoted to a roving vehicle system. It seems reasonable also that, on the later missions, the entry payload might be added to the landed science. Therefore, the Saturn V launch vehicle and Earth-Mars astrodynamic constraints could place an upper limit gross weight of approximately 2,185 pounds on the Rover. If only one planetary vehicle were designed for the Saturn V the Rover gross weight could exceed 4,000 pounds.

A rough measure of the maximum weight of roving vehicles landed on the moon is the MOLAB, designed to be launched on a Saturn V and landed with a modified Apollo LM. This vehicle had a design goal of 6,000 pounds gross weight and constituted essentially all of the useful payload.

Recent analyses of hypothetical Martian and lunar surface missions have indicated the desirability of studying the capabilities of roving vehicles with gross weights ranging from 750 to 900 pounds. Therefore, in this RVMC study, emphasis will be placed on Rovers in this weight range, but extrapolations will also be made to higher and lower weights.

4.1.1.2 COMMUNICATION DISTANCE. Lunar and Martian astrodynamic parameters that affect the control of a landed roving vehicle are listed in Table 4-II. Of the parameters listed, communication distance imposes the most significant constraint on effective Rover control. For a 1973 Type I trajectory to Mars, communication distance at landing would be about 180×10^6 km. The distance would then increase to a maximum of nearly 400×10^6 km nearly 8-1/2 months later. One-way information transit time will thus range from about 10 to 22 minutes. Figure 4-1, adapted from Reference 1, shows the communication range in astronomical units (AU) over the entire 1973—1985 period. ($1 AU = 149.599 \times 10^6$ km.)

The Earth-Moon mean communication distance is 348.4×10^3 km and is relatively constant. Maximum one-way information transit time is about 1.35 seconds.

4.1.1.3 SUN-MARS-EARTH ANGLE. This angle may affect the method of operating on the surface inasmuch as it determines the maximum diurnal period during which both the earth and the sun are visible. As seen in Figure 4-2 both the sun and the earth are visible over the angle α which is $(180-\beta)$, where β is the angle between the Mars-Earth and the Mars-Sun vectors. This is, of course, somewhat simplified since Mars'

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Table 4-II
ASTRODYNAMIC PARAMETERS AFFECTING MOTION CONTROL OF THE LANDED ROVING VEHICLE

Moon	
Gravitational acceleration	1.62 m/sec^2
Gravitational parameter, GM	0.4890×10^4 km/sec^2
Solar day	29.530588 days*
Mean distance from earth	0.384411×10^6 km
Perigee distance	0.356411×10^6 km
Apogee distance	0.406699×10^6 km
Mean angular velocity in orbit	13.2 deg/day*
Inclination of orbit to ecliptic	$5^{o}8' 43.5''$ avg
Apparent angular rate of earth	0.1 deg/hr
Mars	
Gravitational acceleration	3.72 m/sec^2
Gravitational parameter, GM	$0.42830 \pm 0.00008 \times 10^5$ km^3/sec^2
Mean solar day	$24^h 39^m 35.0505^s$
Mean distance from sun	227.8×10^6 km
Minimum earth-Mars distance range	$(56.5$ to $101.5) \times 10^6$ km
Maximum earth-Mars distance range	$(354$ to $401) \times 10^6$ km
Mean angular velocity in orbit	0.525 deg/day*
Inclination of orbit to ecliptic	$1^{o}50' 50.8''$
Apparent angular rate of earth	15 deg/hr

* earth day

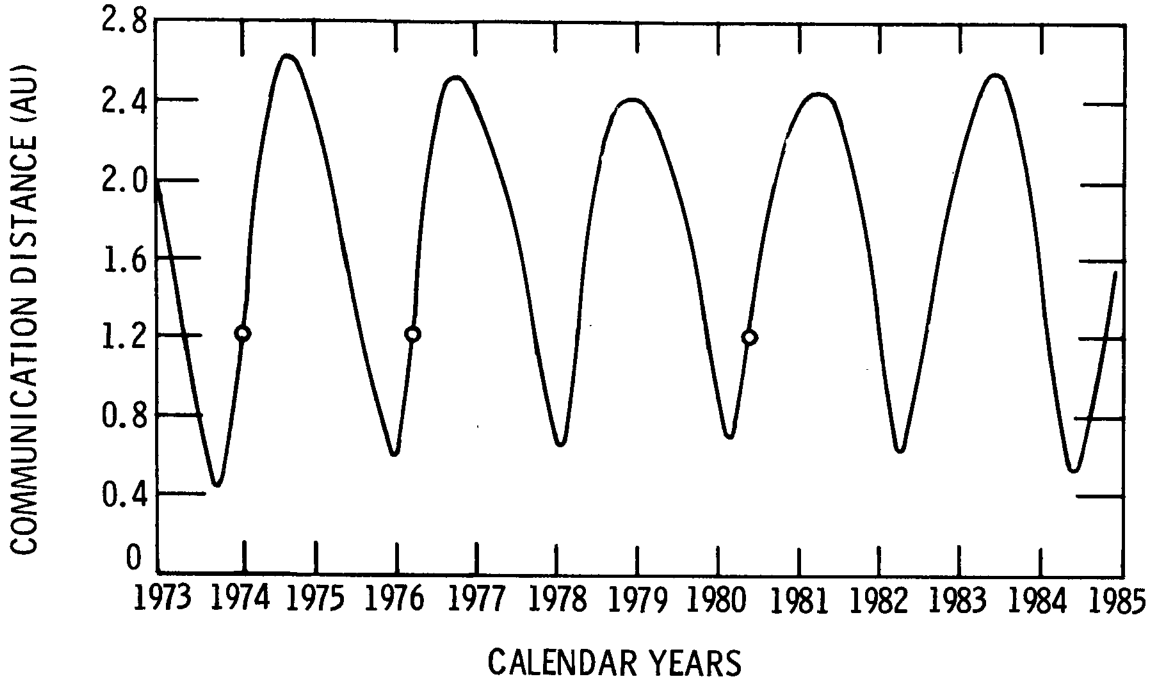

Figure 4-1 Earth-Mars Communication Range

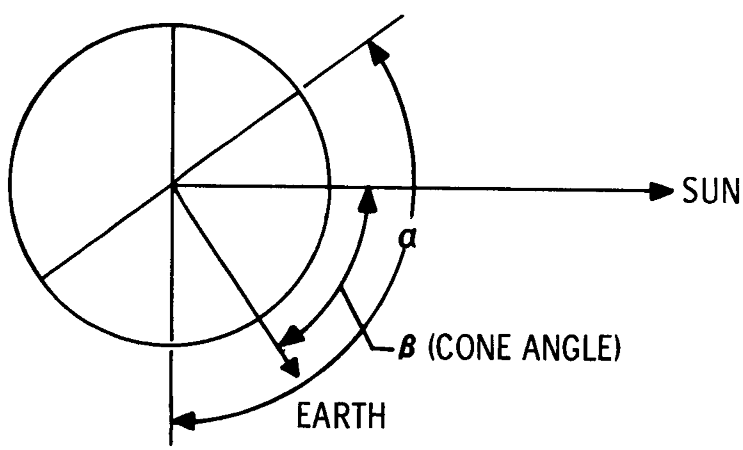

Figure 4-2 Cone Angle

equator does not lie in the plane in which β is measured. The angle β is called the cone angle, and its variation with time for the 1975 opportunity is shown for illustration in Figure 4-3 adapted from Reference 2.

4.1.1.4 LATITUDE OF THE SUB-EARTH POINT. Because the earth does not always lie above the Martian equator, it will not generally be visible for twelve hours per Martian day. In fact, if the landing site latitude deviates very much from that of the sub-earth point, the time during which the earth is visible, and therefore direct communication can occur, becomes quite short; and, of course, if the two latitudes differ by more than 90^{o} the earth ceases to be visible at all. Figure 4-4, adapted from Reference 1, shows the daily time interval during which earth is visible (assuming visibility requires an elevation angle of at least 30^{o}) for sub-earth point and landing point latitudes.

4.1.2 Astrophysical Constraints

Prior to debarking from the landing vehicle the Rover will be exposed to the atmosphere of the survey body and the radiant energy that penetrates the atmosphere. The major constraint presented by the atmosphere involves cooling the heat-dissipating surfaces of the Rover. Other influences include the forces of winds, dust, possible corrosive effects due to chemical reactions with exposed Rover surfaces, and the atmospheric effects on illumination and telecommunications. When the Rover leaves the landing vehicle it will contact the surface of the survey body. The surface characteristics will principally affect Rover locomotion — the composition of the surface may cause degradation of the Rover due to chemical reactions or abrasive wear.

4.1.2.1 CHARACTERISTICS OF LUNAR AND MARTIAN ATMOSPHERES. The lunar atmospheric pressure inferred from optical and radio measurements ranges from about 10^{-9} torr to 10^{-13} torr. Some theoretical calculations indicate that the pressure may be as low as 10^{-16} torr on the dark side of the moon. Listed in Table 4-III are possible sources of lunar atmosphere together with the constituents which probably would be present.

Table 4-III
SOURCES AND PROPERTIES OF LUNAR ATMOSPHERE

Original Atmosphere	Xe, Kr, Ar
Lunar Vulcanism	H_2O, SO_2, NH_3, O, H
Lunar Rocks and Magma	CO_2, HCl, Cl_2, H_2S, CO, CH_4
Meteoric Volatization	Ni, Fe, Si, S, SO_2, H_2S
Solar Wind Accretion	Ne, N, O

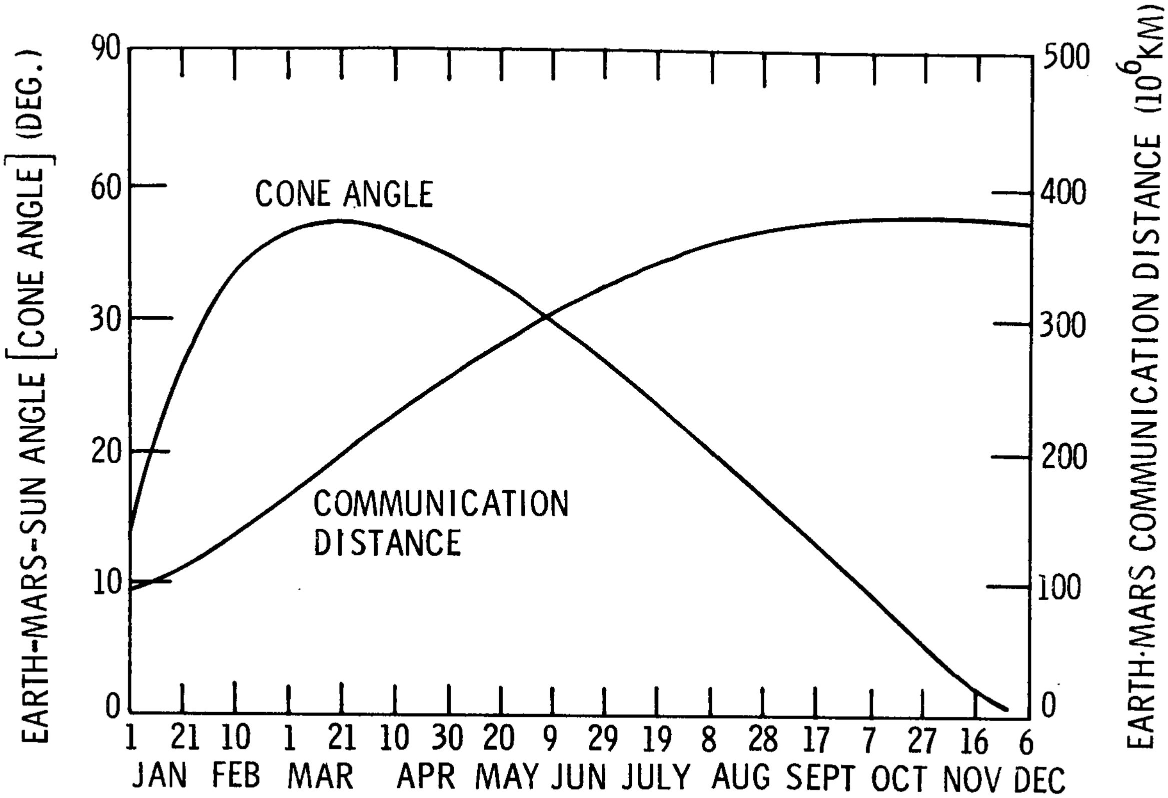

Figure 4-3 Earth-Mars-Sun Angle (Cone Angle), and Earth-Mars Communication Distance vs Time

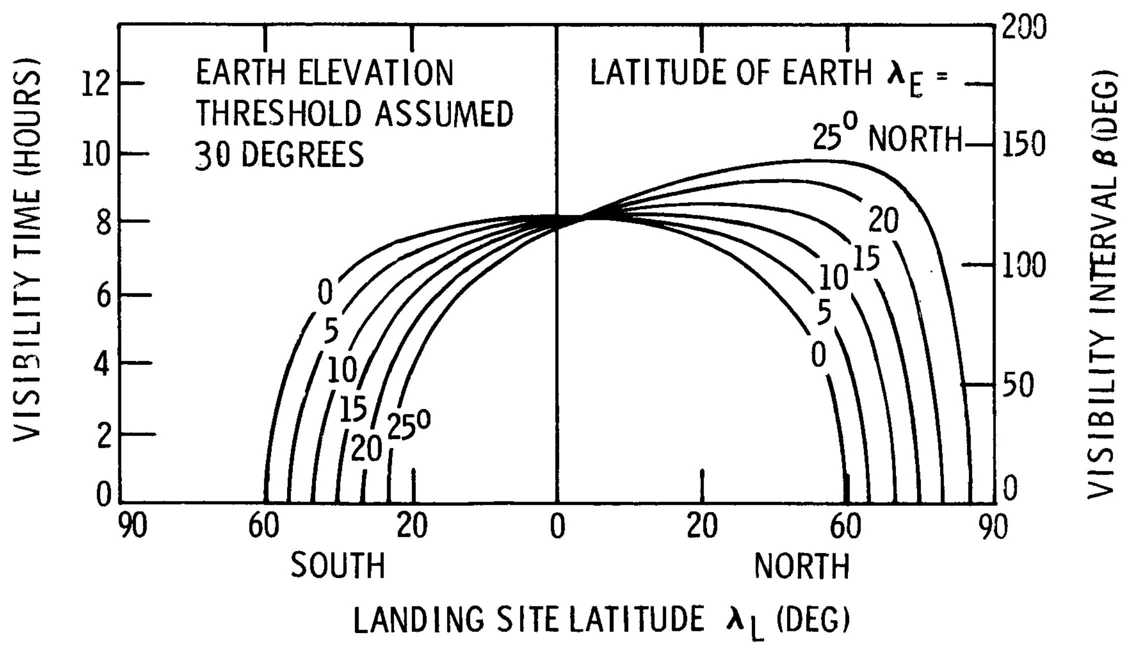

Figure 4-4 Earth Visibility of Lander

Mars surface-atmosphere density is equivalent in magnitude to the earth's atmosphere pressure at 100,000 ft. The surface pressure may be between 4 and 10 millibars and surface winds with velocities up to 220 feet per second may be encountered, with gusts up to 550 feet per second. Carbon dioxide has been selected as the primary component of the atmosphere. Clouds appear in the Martian atmosphere and they generally show a continuous shading of colors that are usually discernible visually. These clouds may be divided into three colors: white, yellow, and blue.

4.1.2.2 CHARACTERISTICS OF THE LUNAR AND MARTIAN SURFACES. Based on observations made during the Surveyor I mission and reported in Reference 3, within 1 to 2 km surrounding the landing site (2.53^{o} S, 43.32^{o} W) the lunar surface is gently rolling and studded with craters ranging from a few centimeters to several hundred meters in diameter, and contains angular fragments that range in size from less than 1 mm to more than 1 m. Dynamic bearing resistance at the touchdown point appears to be 4×10^5 to 7×10^5 dynes/cm^2. The mechanical behavior of the surface appears qualitatively similar to that of a damp, fine-grained terrestrial soil. The integral frequency distribution of craters, normalized to 100 m^2 for sample areas of 6 m^2 and 47 m^2, is shown in Figure 4-5.

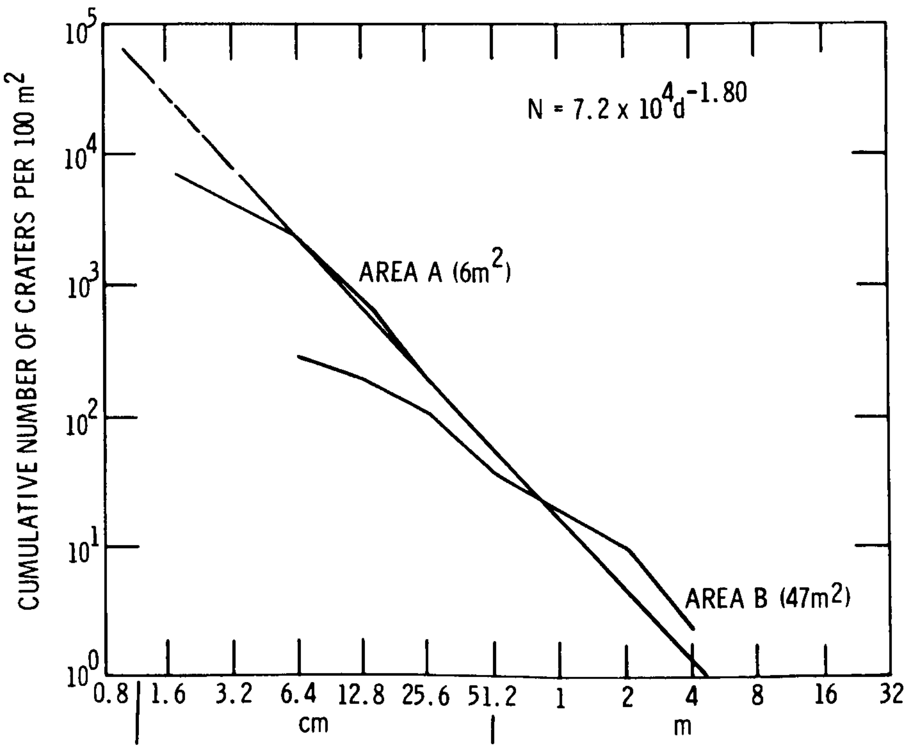

Figure 4-5 Cumulative Size-Frequency Distribution of Craters on Lunar Surface Determined from Surveyor I

An iron oxide composition appears to constitute a significant portion of the Martian surface. The most often mentioned material is the mineral limonite ($Fe_2O_3 \cdot nH_2O$), a ferric oxide polyhydrate. Photographs of Mars taken by Mariner IV indicate that the planet resembles the moon. Thousands of craters, ranging in size from 150 km down to 3 to 5 km, pockmark the surface. The ultimate surface bearing capacity of a loose sandy soil on Mars may range from 0.4 lb/in.^{2} to 1 lb/in.^{2} for a one-foot wide support. Soil cohesion is considered to be in the range of 0.02 to 0.05 lb/in.^{2} (Reference 4).

4.1.2.3 LUNAR AND MARTIAN SURFACE TEMPERATURES. Surveyor I on the lunar surface is exposed to temperature extremes ranging from 260°F to -245°F. The surface of Mars (excluding the polar regions) is thought to vary from approximately 40°F to -10°F (Reference 5).

4.1.2.4 LUNAR AND MARTIAN RADIATION. The visible and infrared portions of the solar radiation spectrum are considered to have first-order effects for purposes of the RVMC study. All other radiation and particle bombardment phenomena are considered to have second or third order effects. Table 4-IV lists lunar illumination and albedo data obtained from Reference 6.

Results of a photometric analysis by RCA[20] show that luminence distributions will not in general resemble visual experience on earth. This is due to the high backscatter of the lunar photometric function. The azimuth angle between the vector from the sun and the vector from a TV camera to the scene has a strong effect on object visibility. The glare pattern below the sun apparently will not exist on the moon due to the lack of specular reflection from the surface. Almost all detail will be lost for low sun elevations in the part of the scene away from the sun.

The color of the bright areas of Mars ranges from reddish tints or bright pink to almost crimson, depending on the particular region. According to Reference 4, the likely range of albedo for the light areas in the visible is 0.15 to 0.20. The solar constant is approximately 0.050 to 0.074 watts/cm^2 depending upon the Sun-Mars distance. Constantly changing atmospheric phenomena (primarily yellow clouds) appear to be the largest unknown factor in planning studies of the surface and atmosphere.

4.1.2.5 LUNAR AND MARTIAN TELECOMMUNICATIONS MEDIA. The absence of terrestrial-type atmosphere, particularly troposphere and ionosphere, prevents communication by scatter or reflection techniques on the lunar surface.

Table 4-IV
LUNAR ILLUMINATION AND ALBEDO

Mean illumination by Sun	13.4 lumens/cm^2
Mean illumination by full Earth	1.35×10^{-3} lumens/cm^2
Mean illumination by crescent Earth	
Phase of Earth	
0°	1.35×10^{-3} lumens/cm^2
30°	0.93×10^{-3} lumens/cm^2
60°	0.56×10^{-3} lumens/cm^2
90°	0.28×10^{-3} lumens/cm^2
120°	0.11×10^{-3} lumens/cm^2
150°	0.02×10^{-3} lumens/cm^2
Mean lunar maria albedo	0.065
Mean lunar continents normal albedo	0.105
Integrated lunar normal albedo	0.073
Solar constant	0.14 watts/cm^2

Similar constraints will apply to Martian surface communications; however, the thin atmosphere may be partially ionized by the Sun. The Martian atmosphere will affect the passage of electromagnetic waves from earth by changing the phase velocity and bending the transmittal waves. These influences will not affect the rate of information flow from Mars significantly. One-way transit time for electromagnetic radiation between Mars and Earth, varies between 3.13 and 22 minutes.

4.1.3 Deep Space Network

All intelligence regarding the performance and status of a lunar or Martian rover must be obtained via the Deep Space Network. The efficiency and reliability of the rover — DSN link will determine the rates of information and command flow and consequently the effectiveness of vehicle motion control. The focus of the RVMC study is on devising systems that can effectively control vehicle motion despite the bit-rate limitations and time delays inherent in the information channels. Information flow rates for the Martian channel are three to five orders of magnitude lower and time delays are about three orders of magnitude greater than for the lunar channel.

4.1.3.1 DEEP SPACE INSTRUMENTATION FACILITY (DSIF). The major problem of deep space communication appears to be overcoming the great attenuation of a signal that occurs because of the great distances it must travel. Fundamentally, the ability of a deep space communication system to track, command, or acquire telemetered data from a vehicle is a function of the ratio of signal to noise level. Design of a system to communicate out to a particular distance is basically a problem of compensating for space losses by transmitter power, antenna gains, and receiver sensitivity. Minimizing noise levels, on the other hand, depends upon many factors, including mainly the avoidance of RF noise sources and design of the receiver preamplifier.

To support Voyager, the DSIF will consist of one network of three 210-foot antennas and a second network of three 85-foot antennas located at 120^{o} intervals in longitude (Reference 7).

Table 4-V lists projected characteristics of the DSIF stations that influence the bit rates for the Martian and lunar channels. Four selectable predetection bandwidths (1 dB) will be available at 10 MHz as follows: 4.5 KHz max., 20.2 KHz max., 420 KHz max., and 2.2 MHz max. The DSIF stations utilize PCM/PSK/PM modulation systems.

Table 4-V
DSIF CHARACTERISTICS

Transmitter power			400 kw
210 ft antenna gain	(2110—2121 MHz)	transmit	60 ± 0.8 dB
	(2290—2300 MHz)	receive	61 ± 1 dB
Beam width		transmit	0.145 deg
		receive	0.135 deg
Receiving system temperature (with maser)			45 ± 10^{0}K

A command system data-processing and transmitter phase-modulation capability will be provided at each Deep Space Station. A command verification-transmission technique will be utilized whereby the incoming command message is verified and translated into the proper spacecraft language, and then is transmitted. During transmission, a bit-by-bit comparison is made for final verification. At present SDS-920 computers are used for telemetry and command data processing, but these machines will be modified to accommodate Voyager requirements. Some limited analog-digital capability for handling analog signals is planned, but significant analog processing (such as analog TV, for example) is not foreseen for the Voyager era.

4.1.3.2 GROUND COMMUNICATION SYSTEM (GCS). The Ground Communications System consists of voice, teletype, and high-speed data circuits between each overseas station, the Cape Kennedy Station and the SFOF. The functions of the GCS are: a) to relay data and information obtained by the DSIF to the Space Flight Operations Facility, and b) to relay status information, operational instructions, and spacecraft commands from the SFOF to the DSIF. By 1973 it is expected that all GCS overseas communications will be satellite-derived. The communication capability of a typical overseas DSIF station with SFOF will be as follows:

1. Teletype: 4—6 circuits, error rates 10^{-5}
2. High speed: 1—2 circuits, 2400 to 4800 b/s, error rate 10^{-5}
3. Voice: 2 circuits
4. Wideband: 4.5 MHz video one-way from DSS to SFOF (time shared)
5. Wideband digital channel: 50,000 b/s

Command rates will be 100 b/s.

4.1.3.3 SPACE FLIGHT OPERATIONS FACILITY (SFOF). The Space Flight Operations Facility is a data processing entity which will allow, for two or more missions simultaneously, the efficient coordination and direction of mission activities; command, monitor, and control of spacecraft performance; acquisition, analysis, and evaluation of mission experimental data; two-way communications between earth and spacecraft; and finally, tracking and position data processing over planetary distances.

Handling the enormous quantities of data derived from the tracking, telemetry, and operation of a spacecraft requires a central control agency which can process and display received information reliably and quickly, can exert coordinated command functions via worldwide communications network and spacecraft facilities, and can provide for efficient implementation of the personnel effort required for space missions.

Different missions impose different requirements upon the data processing complex. The SFOF must be specifically configured to handle each mission. However, the basic hardware functions remain essentially the same. It is expected that the change in configuration will be accomplished by software modifications which can be carried out quickly and at a fraction of the cost involved in hardware changes.

In the case of a roving vehicle mission, work stations would, insofar as possible, be configured from existing hardware for locomotion control, sensor control, telecommunications control, and monitor/command functions as required by mission objectives.

4.2 MISSION CHARACTERISTICS

As noted earlier, the systems design of any RVMC system must take into account the mission of the roving vehicle. Accordingly, an attempt was made early in this study to postulate a set of missions upon which to base the design and evaluation of candidate systems. However, it soon became apparent that any attempt to do this would run the risk of prematurely and perhaps unnecessarily restricting the scope of the study.

For this reason, the attempt was abandoned in favor of an approach which would characterize missions in terms of functional elements, combinations of which could be used to describe any specific mission that might be proposed. The following describes the elements which directly affect the control of the roving vehicle.

Two basic functions of the control system can be identified at the outset.

F1) To effect safe transfer of the roving vehicle to a specified point

F2) To orient the vehicle in a prescribed manner with respect to another (stationary) object and perhaps to effect some sort of physical connection with it.

The means of accomplishing F1 are directly influenced by the mode of choosing the specified point and by the parameters used to define the point. The destination may be chosen by one of three methods.

M1) Experimental points are pre-programmed based on a priori knowledge, e.g., Orbiter pictures, and/or experiment requirements.

M2) The earth-based mission control station makes all decisions regarding destinations based on mission requirements and prior data returned from the mission.

M3) The control system chooses the destination based on programmed decision processes and vehicle-borne sensors.

These methods refer to the choice of major destinations which might involve a lengthy sequence of minor intermediate destinations, rather than to detailed control decisions. Further, it seems reasonable that both M1 and M3 should include not only M2 but also the capability of re-programming by earth command during the mission.

Mode M1 might be used when detailed a priori knowledge of points of interest exists or when the location of experimental packages in a specific geometrical array is desired. Mode M2 is appropriate when a priori knowledge of points of interest is scanty, when missions are of a sampling type, or when system constraints prohibit the degree of automaticity required of M1 or M3. Mode M3, the most sophisticated, is attractive when the conditions appropriate to M2 exist, but when operating windows or data rates seriously degrade mission efficiency under M2. Here the control system must locate and evaluate points of interest, and automatically devise a plan to reach these points.

The destination may be specified in a number of ways resulting in different control requirements.

C1) Destination coordinates (range and bearing) are specified, perhaps with a given CEP.

C2) The range is specified, but the bearing is not critical.

C3) The bearing is specified, but the range is not critical.

C4) The destination is specified in terms of some experimental requirement other than range or bearing (e.g., gain a high point).

C5) The destination is a point previously occupied by the roving vehicle.

A concomitant of the ability to reach the destination, however specified, is the ability to navigate, i.e., to determine the roving vehicle's current location. For some missions the navigation requirements will be determined by the manner of specifying the destination. For others, the a posteriori ability to locate experimental points accurately is more important than the ability to reach a specific point. This leads to two general navigational situations.

N1) Navigation requirements are no more stringent than the requirements implied by the description of the destination.

N2) Navigation requirements are significantly more stringent than those implied by the destination description.

Task F2, orientation of the vehicle in a prescribed manner with respect to another object, and possible physical connection with that object, has not been developed in detail at this time. It is noted, however, that this task may require precision control not unlike that required to traverse extremely rough, complex terrain.

It is axiomatic that, in performing either F1 or F2, the safety of the vehicle is paramount. This implies that the vehicle control system incorporate the minimum capability to detect obstacles which constitute a hazard to safety and to pick a path around such obstacles. The sensors required to assure this capability are assumed to be carried on the vehicle.

In the generation and execution of a path plan to reach a given destination efficiently, routine decisions may be carried out in either of two basic ways

D1) Decisions are routinely made by the earth-based operations control station.

D2) Decisions are routinely made on the vehicle in accordance with preprogrammed (possibly self-adaptable) instruction.

The considerations leading to M1 and M3 would generally rule out D1, since a control system which automatically selected the destination points would hardly be likely to rely upon earth control for routine path planning. However, D2 is compatible with any of the three modes M1, M2, or M3.

Subsequent sections show how these generic mission characteristics may be used to develop system functional requirements and function flow analyses. In conjunction with specified terrain models, they permit the detailing of requirements to the level required to configure candidate systems.

4.3 TERRAIN CHARACTERIZATION

Three terrain models representing three essentially different vehicle control problems were derived and are described below. In keeping with the generic nature of the initial effort on the study, these models are not defined quantitatively at this time, although means of doing so are discussed below. The models are not intended to represent known lunar or planetary terrains but simply to represent a range of terrains which conceivably could be encountered in terms of characteristics most likely to affect control, i.e., slopes, roughness, soil strength, photometric properties, etc. Qualitative descriptions of these terrains follow:

T1. This terrain consists of a gently rolling terrain having no sharply defined features. Occasional slopes exceeding the capability of the vehicle may be encountered and must be guarded against, but, for the most part, vehicle control will consist of confirming the safety of a chosen course of action and of choosing paths for maximizing mission efficiency from the standpoint of either velocity or energy consumption. Typical of this model is the terrain at the impact point of Ranger 7.

T2. This terrain consists of Model 1 overlaid with sharp features (rocks, cliffs, crevices, holes, etc), most of which are within the capability of the vehicle to negotiate. The model contains a sufficient number of hazards to mobility that care must be routinely exercised, but a safe path is readily found. Most control decisions will consist of verifying safe passage and choosing between obstacle negotiation and obstacle avoidance.

T3. This terrain is a more severe version of Model 2, where the frequency of hazardous features is so great as to constitute a continuous threat to vehicle safety, and a safe path may even be nonexistent. Here, control activity must be routinely concerned with evaluating the degree of threat to vehicle safety with the ever-present possibility that an erroneous decision will be not merely inefficient, but may terminate the mission.

In all three of the above models the basic matrix consists of a non-cohesive or only slightly cohesive soil of varying bearing strength from about 1 to 10 psi. The photometric properties of the background matrix may be taken as those given for the moon (Reference 7). Lacking any definitive photometric function for Mars it is assumed for this study that the same function holds for Mars as well. Background albedo for the moon varies from about 0.06 to 0.11 with an average of about 0.07. For Mars the albedo is assumed to be higher, about 0.15 to 0.20.

There are many methods which may be used to characterize surface properties quantitatively. Terrain such as described in Model 1 may be represented by a contour map which provides quick recognition of general terrain features and brings out unique topographical features of a particular region. However, it is applicable only to that region and gives information which is not of interest to general mobility while failing to provide a simple quantitative characterization of the aspects which do affect mobility.

Another method, which recognizes the statistical nature of terrain characterization is the slope histogram or slope probability distribution. Such a characterization depends strongly upon the sampling interval used, a sampling interval of the order or one to ten vehicle lengths being required for energy calculations. However, it fails to provide sufficient information for control purposes because it gives no information about the dependence of the slope at any given point upon the slopes at nearby points. This is not a serious limitation on a scale of a kilometer since such dependence is probably tenuous at this distance. The limitation on the scale of a few vehicle lengths is serious, however, especially in the case of gently rolling terrain where abrupt changes in terrain are unlikely.

Another similar approach which has been taken is to characterize the probability distribution of the derivative of the slope (or the curvature). This approach suffers from the same problem as analysis of slope statistics, namely, that it fails to account for correlation between the curvature at adjacent points. Since the correlation is probably less for the curvature than it is for the slope the latter characterization is in this sense preferable. However, this characterization is very cumbersome in use, particularly in generating a terrain model.

An approach which accounts for the statistical nature of the terrain and also incorporates the effects of correlation is one which characterizes the terrain in terms of its power spectral density, which is derived as the Fourier transform of the autocorrelation function under certain assumptions which can usually be satisfied practically. This approach provides a quick quantitative comparison between terrains. Previous analyses of a wide variety of terrains indicates a tendency for the spectral density of all these terrains to have approximately the same form, viz., they follow an inverse power relationship with spatial frequency. A rough approximation is obtained by using a minus 5/2 power law. The rms roughness in the size range of interest is simply the square root of the integral of the spectral density over the corresponding range of spatial frequencies. Thus, a vehicle having an overall length of two meters and a wheel diameter of one-half meter might reasonably be affected by terrain roughness in the range of 0.2 meter to 20 meters, corresponding to a spatial frequency range of .05 to 5 cycles per meter.

Small craters on the surface of the moon have been considered by several investigators since the Ranger series of missions. These have been characterized in terms of their cumulative frequency distribution per unit area by expressions of the form $N = aD^b$ where N = number of craters with diameters greater than D per unit area and a and b are empirically determined constants. The exponent, b, consistently takes on a value of approximately -1.8. Crater distributions consistent with terrain Model 1 would result from use of $a \cong 10^5$; distributions consistent with Model 2 from $a \cong 5 \times 10^6$; and distributions consistent with Model 3 from $a \cong 10^8$.

It appears that useful terrain models could be generated by computer from the above considerations. Starting with an underlying terrain having a spectral density over the range of interest which can be characterized by two parameters (level and slope), one could overlay this first with craters having a size distribution characterized as above and a Poisson area distribution. This would be followed by a particle overlay having appropriate size distribution and Poisson area distribution.

More thought must be given to this approach before it would be useful. Among the areas that need to be further developed are those of spectral characterization in two dimensions and generation of two-dimensional models from an appropriate characterization. Another is the problem of a rationale for the superposition of two or more craters or rocks at the same point or at points which are relatively close together.

4.4 SYSTEM REQUIREMENTS

In order to provide a basis for configuring representative candidate Roving Vehicle (RV) systems, a study was made of the spectrum of functional requirements imposed by the above general mission characteristics, as they apply to the control of a roving vehicle operating on each of the three surface models and under the basic astrodynamic constraints described in Section 4.1.

The major constraints imposed by astrodynamic considerations are those of (1) telecommunications windows, which may restrict total system communications traffic in the case of Mars to as little as six hours per day and RV control traffic to considerably less; (2) telecommunication distances, which may introduce delays of up to twenty minutes in one-way transmission times as well as serious signal attenuation; (3) Martian diurnal cycles, which may reduce available system operating time by approximately one half.

Other constraints exist (e.g., the lack of a magnetic field on the moon or Mars), but since they may be dealt with by relatively minor modifications of system design they are not treated at the present level of study.

The general functions stated in Section 4.2 above were used as a starting point for defining roving vehicle control system requirements. System requirements imposed by these functions may be stated at the highest level of generality, and function flows may be constructed relating the requirements to system operating procedures. As the implications of additional system factors (terrain models, destination characteristics, etc.), are considered, system requirements and function flows can be specified at successively lower levels, until it is possible to make meaningful assignments of system hardware and software. This process is carried out in the following treatment for a system capable of accomplishing function F1 under mission characterization C2 over Terrain T1. Top level RV system requirements for the two functions described are given in Table 4-VI.

Since the requirements for Function F2 include those for Function F1, a single function flow may be used to include both. The flow starts with selection of a destination (either point or object), and terminates when mission success has been satisfactorily evaluated. Figure 4-6 gives the function flow for these functions.

Table 4-VI
TOP-LEVEL SYSTEM REQUIREMENTS FOR A ROVING VEHICLE SYSTEM CAPABLE OF ACCOMPLISHING TWO BASIC TASKS

Function	A requirement exists for an RV which can:
1. To move scientific instruments safely from Point A to some specified Point B.	(1) transport the desired instrumentation; (2) negotiate the required surface safely in response to preprogrammed or earth-communicated control; (3) identify Point B and approach it in the desired manner; (4) return sufficient status information to earth to allow assessment of the transport mission success;
2. To accomplish Function F1 and to orient with respect to, and/or mate physically with a stationary object in a prescribed manner.	Accomplish (1) through (4) and (5) detect and report the location of the stationary object; (6) approach the object safely with the required accuracy; (7) orient in position and azimuth with respect to the object; (8) achieve physical contact; (9) return sufficient status information to earth to allow assessment of mating mission success.

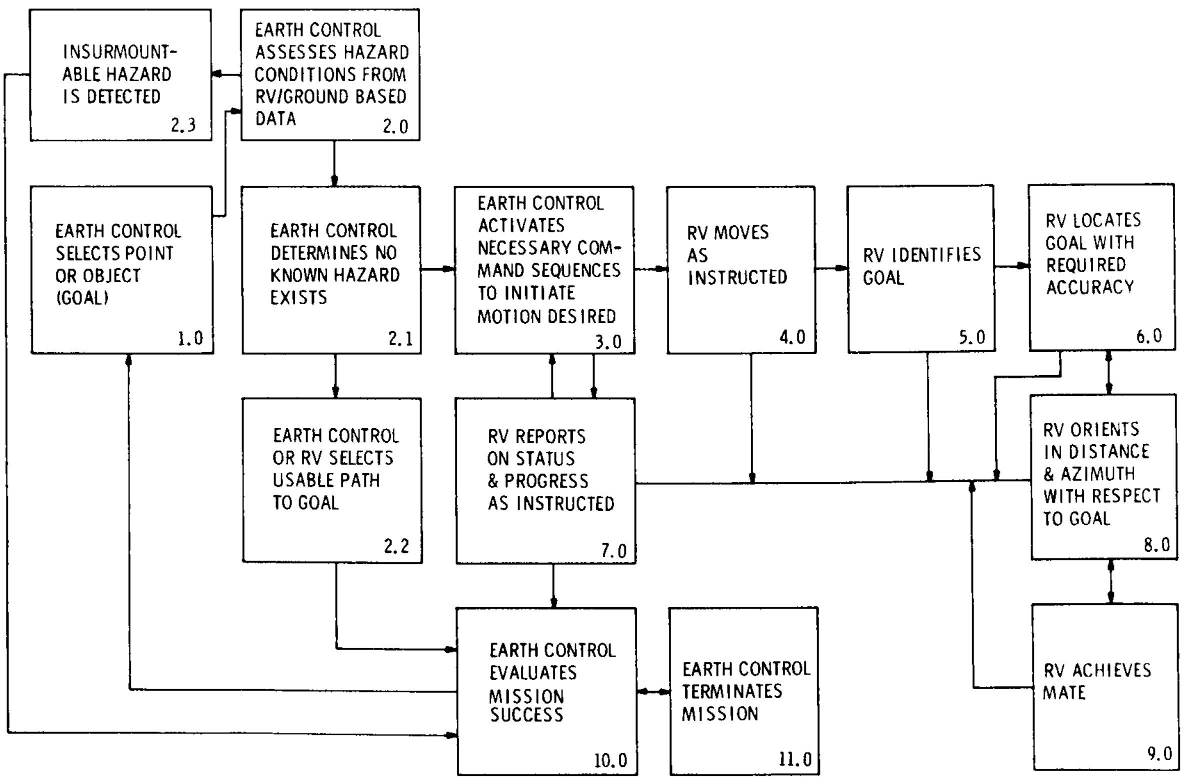

Figure 4-6 Function Flow for Top-Level Requirements for Function F1

At successively lower levels of analysis the basic functions must be interpreted in the light of constraints imposed by more detailed mission characteristics. The nature of Function F1 may be specified in greater detail, for example, by the characterization of the destination point, as shown in Table 4-VII.

The Function Flow which reflects the constraints of C2 on Function F1 are given in Figure 4-7.

Before assigning functions to hardware or software, it is necessary to consider the effects on mission success of the terrain over which the vehicle may be required to operate. The system requirements imposed by one model of terrain is given in Table 4-VIII.

From the third-level function flow of Figure 4-8, preliminary assignments in terms of hardware and software can be made. These are summarized in Table 4-IX. Other constraints which affect the choice of configuration of a control system may be either self-imposed from experimental conditions or dictated by the astronomical constraints mentioned earlier. Navigation requirements for mapping, for example may be met by combining the capabilities required for more than one control category. Duty cycle and decision mode are likely to be dictated more by astronomical considerations. Addition of these considerations to the function flows of Level Three will allow first-cut assignments of the functions to hardware or software implementation, and, eventually, their allotment to man or machine execution.

4.5 SUBSYSTEM STATE-OF-THE-ART

4.5.1 Sensors and Information Display

There are a number of candidate sensor and display subsystem configurations for exploration of the moon and planets using a remotely controlled vehicle. Figure 4-9(a) is a functional block diagram of a typical simple system. Information concerning vehicle/terrain relationships is transmitted to earth in the form of video information, sun compass readings, clinometer readings, odometer readings and range and bearing from the landing vehicle. Engineering data such as vehicle component temperatures, electrical conditions, camera orientation, steering position and power reserve are sensed and transmitted to earth. Additional video and miscellaneous measurements may be made for scientific purposes. In addition, feelers, tilt and roll switches, or similar sensors may be used to stop the vehicle without earth command if the vehicle encounters a hazardous condition. On earth the images and other data are analyzed and appropriate commands transmitted to the vehicle.

Table 4-VII
SECOND LEVEL ROVING VEHICLE (RV) SYSTEM REQUIREMENTS FOR FUNCTION F1

C2: The range (ρ) of B is specified with permissible error	C3: The bearing (θ) of B is specified with permissible error	C1: The coordinates (ρ, θ) of B are specified with a given CEP	C5: B is a point previously occupied	C4: B is set by experimental requirements
1. Earth control must be able to command RV to proceed in a manner which results in an increasing distance from Point A. 2. RV must be able to respond adequately. 3. RV must be able to report data which will enable RV distance from A to be determined. 4. Earth control must be able to stop vehicle when desired.	1. Earth control must be able to command RV to go in any given direction. 2. RV must be able to respond adequately. 3. RV must be able to report data which will enable RV azimuth from A to be determined. 4. Earth control must be able to stop vehicle when desired.	1. Earth control must be able to command RV to go in any given direction in a manner which results in an increasing distance from Point A. 2. RV must be able to respond adequately. 3. RV must be able to report its position with required accuracy. 4. Earth control must be able to stop vehicle when desired.	1. The requirements of C1 must be satisfied. 2. Any cumulative error in position determination over n intermediate points of the traverse must not exceed allowable error in position determination of Point A on return of RV. 3. Earth control must be able to stop vehicle when desired.	A system that can accomplish C1 can accomplish C4 if the experimental requirements can be reflected by specifying coordinates of the RV. For other experimental requirements the necessary system requirements must be separately specified.

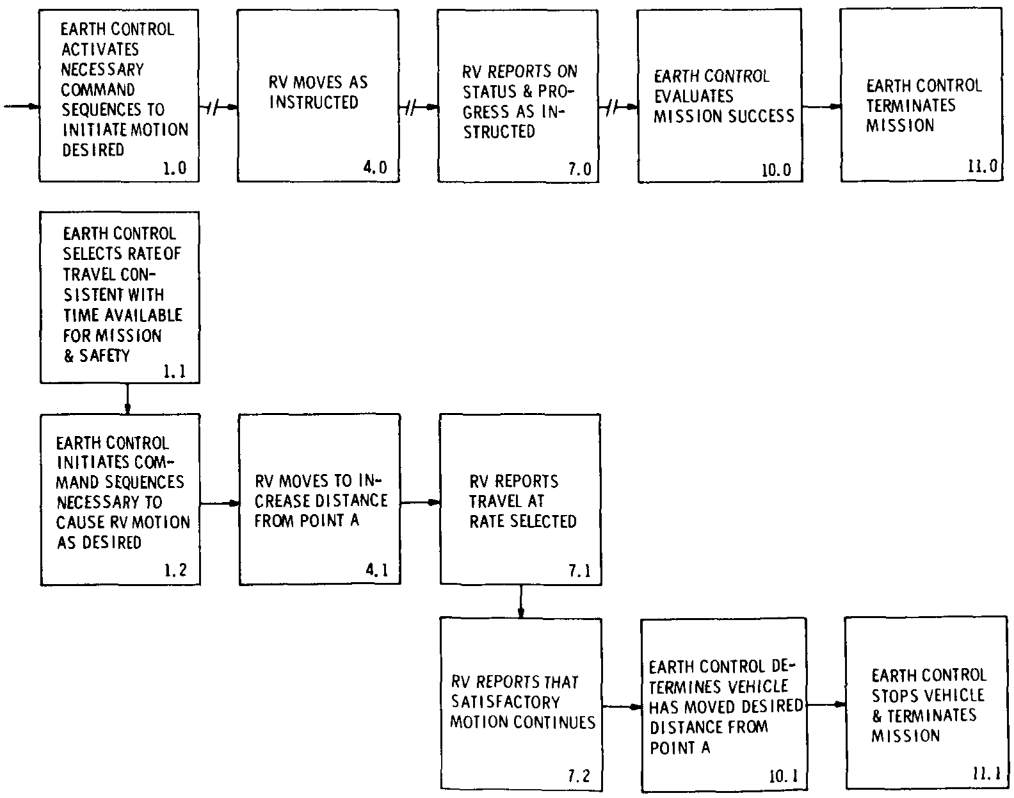

Figure 4-7 Function Flow for Second-Level Requirements for Function F1; Mission Goal is to Achieve a Specified Distance from Point A.

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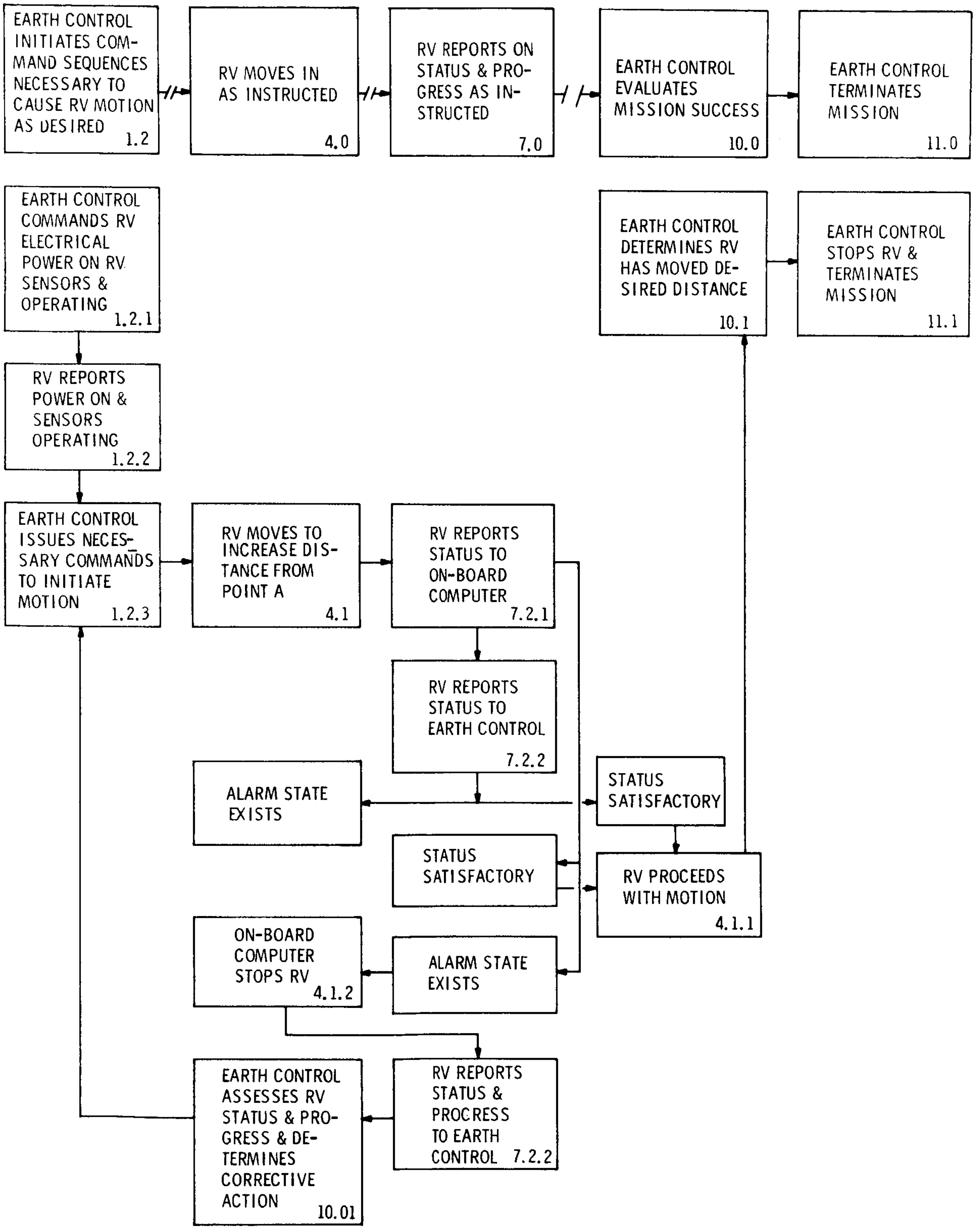

Figure 4-8 Function Flow which Reflects Constraints of Terrain T1 on Destination Characteristic C2 and Function F1

Table 4-VIII
THIRD-LEVEL SYSTEM REQUIREMENTS IMPOSED BY TERRAIN MODEL 1 FOR FIVE DESTINATION CHARACTERIZATIONS

Terrain I: Bland terrain with only occasional slopes exceeding the capability of the vehicle

C2	C3	C1	C5	C4
1. RV must be able to sense (a) Velocity (b) Pitch angles (c) Roll angles (d) Wheel slippage 2. RV must have "stop" capability if (a), (b), (c), or (d) in conjunction with (a) above exceeds preset values. 3. RV must be able to (a) turn (b) back up (c) brake 4. RV must return sufficient data for earth control to determine its distance from A within allowable error.	1. RV must have capabilities 1, 2 and 3 of C2 2. RV must return sufficient data for earth control to calculate its aximuth from A within allowable error.	1. RV must have capabilities of C2 and C4. 2. Meet the error requirements in achieving Point B within the CEP specified for C1.	1. RV must have the capabilities of C1. 2. The cumulative error in position determination over the N intermediate points of the traverse must not exceed allowable error in position determination of Point A (starting point) on return of RV.	1. If system can accomplish C1 it can accomplish C4.

Table 4-IX
PRELIMINARY HARDWARE/SOFTWARE ASSIGNMENTS FOR FUNCTION F1 MISSION CHARACTERIZATION C2, OVER TERRAIN T1

Roving Vehicle Hardware	Roving Vehicle Software	Ground Hardware	Ground Software
RV state sensors Transmitter/encoder with state sensor reporting capacity Command receiver/decoder On-board computer, logic and hardware to accomplish functions listed in column 2	RV → earth communications link Communications link between state sensors and on-board computer On-board computer capability to: (a) turn sensors on/off (b) report sensor states (c) enable motive power at earth command (d) enable motive power, on-board command (e) report Rover status to earth (f) detect and identify alarm state (g) report alarm state to 1. on-board computer 2. earth control (h) disable motive power/apply brakes at computer or earth command	Command transmitter/encoder Indicators for power and sensor states Receiver/decoder Earth-based computer, logic and hardware to accomplish functions listed in column 4	Earth → RV communications link Capability to display sensor states, power states and motion states of RV, including alarm states

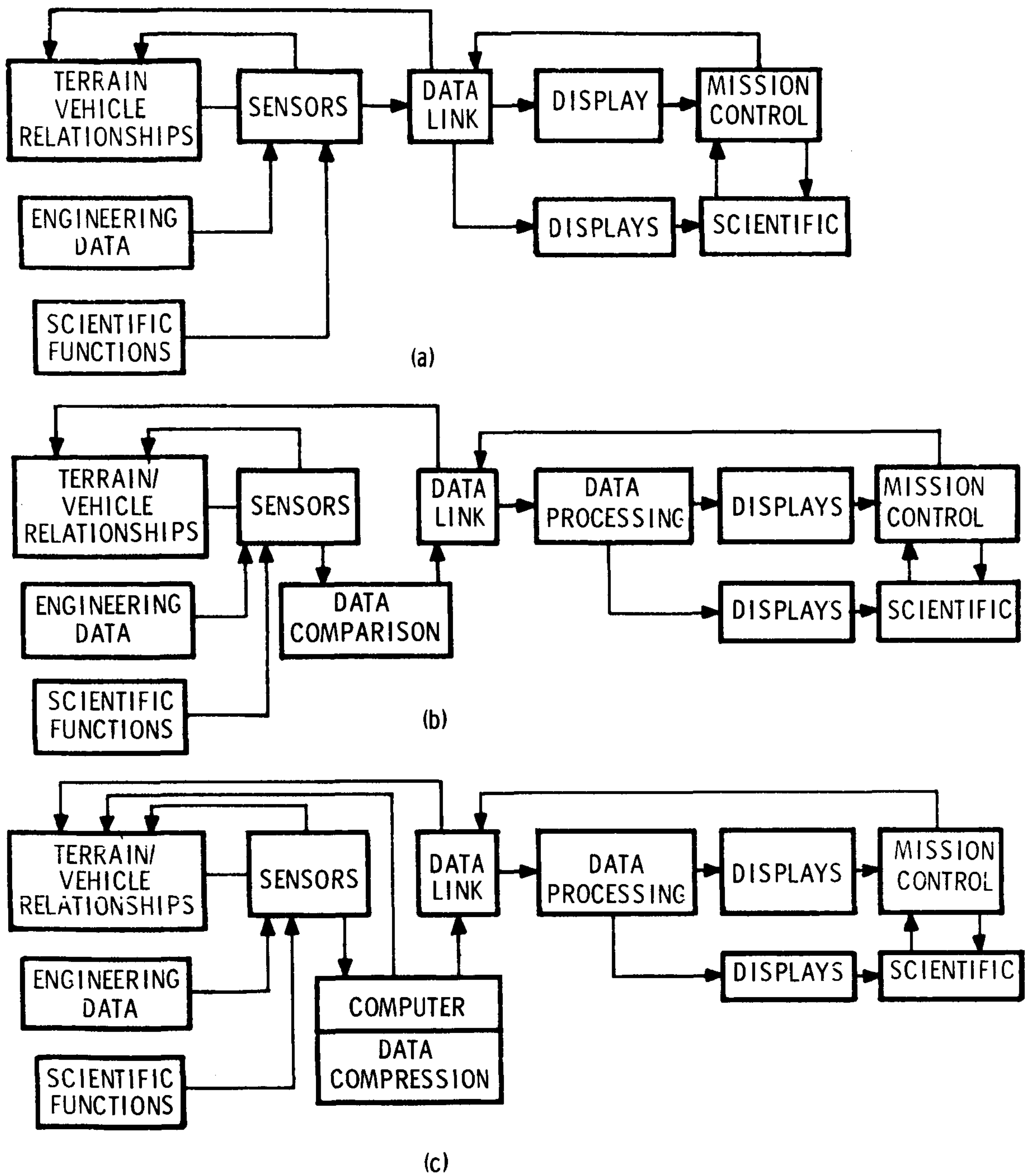

Figure 4-9 Typical Sensor and Display Subsystem

Figure 4-9(b) is essentially the same, except that data compression is provided to limit the amount of data transmitted to the earth by various techniques to be discussed later in detail.

Figure 4-9(c) shows the addition of a computer which, in addition to data compression, can perform analysis of images and/or other data to control the vehicle directly. This approach may be carried to rather high levels of sophistication, as exemplified by work now being done at MIT.[8] For example, among other approaches, MIT proposes the reduction of pictures to line drawings which can be transmitted to earth users at a higher compression ratio than unprocessed video.

Figure 4-9 configurations assume that the roving vehicle is operated independent of the lander. However, the lander might include an imaging system and/or range and bearing equipment for observation of the roving vehicle. From an information standpoint an advantage of navigation control from the lander is that only the vehicle position and orientation are changing in the field of view. Positional accuracy would be better than with dead reckoning from the vehicle. Disadvantages are obscuration effects and curvature of the terrain for great distances. This might be a useful approach during the earliest stages of a mission to help in the development of technique.

Figure 4-10 shows functional block diagrams for existing space imaging systems. In Figure 4-10(a) a two-dimensional image is formed and stored on a vidicon faceplate. The faceplate is scanned with an electron beam and the one-dimensional signal transmitted simultaneously. The image is erased and the process repeated for the next frame. This method has been used on Ranger and Surveyor and has been proposed for a modified Surveyor for Mars by Hughes Aircraft Co.[9]

In Figure 4-10(b) a 2-D image is formed and stored on a vidicon faceplate. The faceplate is scanned with an electron beam and the 1-D signal stored for later transmission. The image is erased and the process repeated for the next frame. This was used on Mariner IV and was proposed for a Mars Orbiter by The Boeing Company.[10]

In Figure 4-10(c) a 2-D image is formed on film. The film is developed and placed in storage for later readout. It is read out by electro-optical-mechanical scanning (CBS Photoscan System) and simultaneously transmitted. It is used on Lunar Orbiter and has been proposed for a Mars Orbiter by JPL.[11]

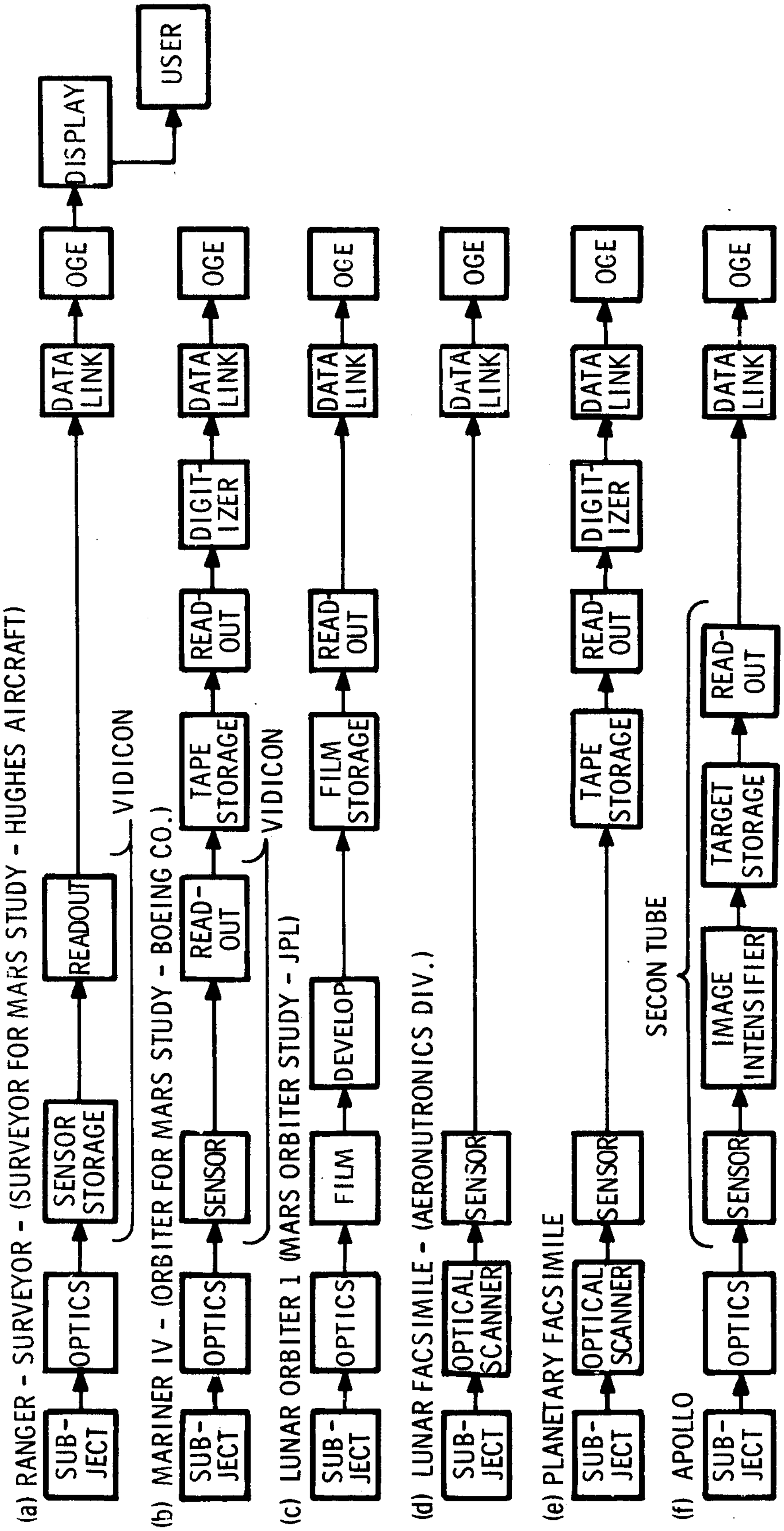

Figure 4-10 Existing Space Imaging Systems

In Figure 4-10(d) the subject is scanned point by point with an optical/mechanical scanner and sensed with a photosensitive device. The resulting 1-D signal is simultaneously transmitted. This system has been developed by the Aeronutronic Division of Philco Corp.[12] Some space missions may not permit transmission at the same rate or at the same time the subject is being scanned. In this case a buffer storage could be added as shown in Figure 4-10(e). In Figure 4-10(e) digitizing could be done before storage.

Figure 4-10(f) uses the Westinghouse Secon camera tube for the Apollo system. It incorporates an image intensifier for sensitivity to low light levels. Whereas the Surveyor uses time integration for imaging with Earth shine illumination, Apollo will require a higher frame rate and thus greater sensitivity.

All of the systems shown in Figure 4-10 could have a data compression block added. Basically, data compression permits transmission of information with more efficient use of power and bandwidth.

A strip mapping type of imagery could be accomplished in many ways. Thus the imaging system would provide a scan of the subject in one dimension and vehicle movement would provide the scan in the other dimension. This would have the advantages of lengthening image acquisition time and of providing a continuously developing image of the terrain being traversed. Disadvantages are that images are spatially incoherent without the use of sophisticated corrections for variations in orientation of the camera platform and that a fairly straight line path would probably be necessary. A hybrid system with an option of normal scanning or strip-map-type scanning might have advantages, since during motion, a nonredundant strip map could be generated.

In addition there are many approaches to reducing the amount of information to be transmitted by pre-processing of video or other data. Figure 4-11(a) shows the MIT system[8] where the output of a pair of stereo television cameras is processed in an on-board computer. The computer performs such functions as contrast enhancement, contour detection and stereo interpretation both to control the vehicle and to provide simplified visual information for transmission to earth.

In Figure 4-11(a) analysis is based on information which is one-dimensional and which has undergone degradation due to television distortion, sampling, etc. In theory, at

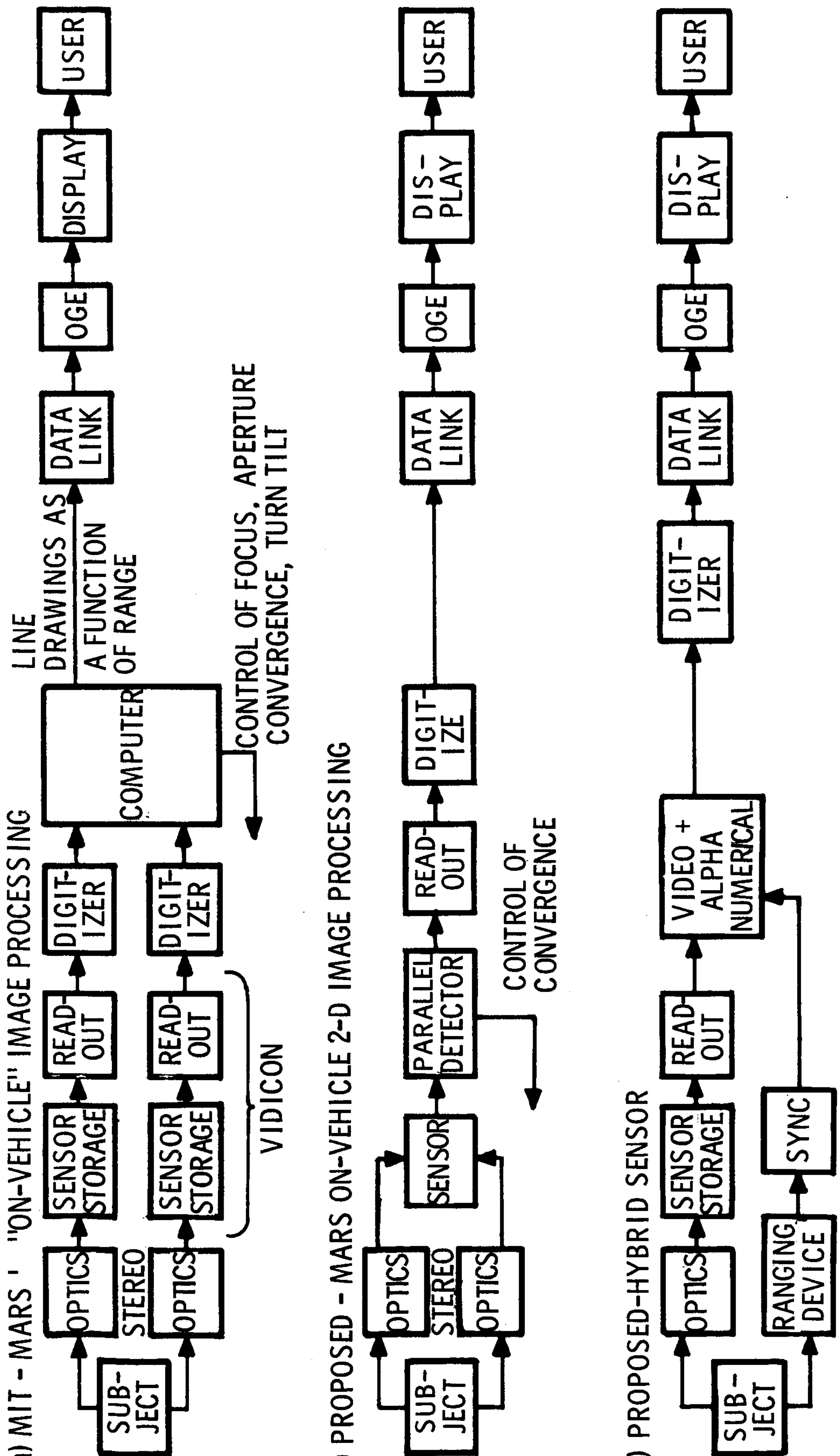

Figure 4-11 Proposed Space Imaging Systems

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least, stereo comparison and contour outlining could be done at the point where the imate is still two-dimensional. This would permit production of much higher quality range and other information. One such configuration is shown in Figure 4-11(b).

Figure 4-11(c) shows a hybrid configuration. A ranging device of high accuracy is used to provide information to be superimposed on a video image of much lower quality than that which would be required of a stereo pair for determination of range on earth.

4.5.1.1 SENSORS. Nonimaging sensors applicable to remote control of lunar and planetary vehicles are given in the following list, together with state-of-the-art performance values.

Solar compass	± 1 degree
Odometer	± 5%
Clinometer	± 1 degree over ± 45°
Tilt and roll switches	< 1 degree
Bumper switches	<< 1 inch
Optical ranging by triangulation	< 1 inch to 10 feet

Devices are, of course, available to give much higher accuracy if required. The values given are those for equipment chosen to meet requirements such as those for SLRV with minimum weight, volume, power, analog-to-digital conversion equipment, and demands on the communication link.

Figure 4-12 is a tabulation of existing and proposed image sensors and important parameters related to system design.

4.5.1.2 SENSOR DATA PROCESSING METHODS. Because of constraints on the rate of video and other data transmission from exploratory missions on the moon and particularly the planets, it is necessary that only required information be transmitted and that this be done in the most efficient manner possible.

The large number of studies directed toward this end are in the two areas of minimizing the amount of data to be transmitted and of data compression.

Minimizing the amount of video information to be transmitted can be accomplished by preselection and preprocessing.

	SYSTEM	Camera	Active Lines	Hor. Resolution	Vert. Resolution	Exposure (Seconds)	Frame Readout Time (Seconds)	Frame Time (Seconds)	Number of Picture Elem.	Grey Levels	Total Bits Per Frame	Face Plate Dynamic Range (Foot Candles/Second)	Scene Dynamic Range (Foot Lamberts)	Residual Image	Geometrical Linearity	Photometric Accuracy	Size Stability	Centering Stability	Fiducial Marks	Color Filters	Aperture	Field Angle	Power (Watts)	Weight (Pounds)	Vol. (Cu. In.)
MOON	Ranger 3, 4, 5	1" Vidicon	200	200	150	.020	10		*4 x 10^4	*64	*2.4 x 10^5	.3-.01	<2700	<10%	1%	±20%			Yes	No					
MOON	Ranger 6, 7, 8, 9 (F)	"	1152	700	700	.005	2.56	5.12	*1.3 x 10^6	*64	*8.4 x 10^6	.68-.004	<2700	<17%	1%				Yes	No	f/1 f/2	25° 8.4°	18.5	15	
MOON	" (P)	"	300	200	200	.002	0.2	0.84	*9 x 10^4	*64	*5.4 x 10^5	.27-.003	<2700	<10%	1%				Yes	No	f/1 f/2	6.3° 2.1°			
MOON	Surveyor 1 (600 Line)	"	600	600	420	.150	1.0	3.6	*3.6 x 10^5	*64	*2.16 x 10^6	.001-.6	.008-2600	6%	1%		<6.5%	<1.5%	5 x 5 Dots	Red/Green/Blue	f/4 f/22	6.43° 25.3°		16.1	
MOON	" (200 Line)	"	200	200	140	.150	20	60.8	*4 x 10^4	*64	*2.4 x 10^5	.001-.6	.008-260	6%	1%		<6.5%	<1.5%	5 x 5 Dots	Red/Green/Blue	f/4 f/22	6.43° 25.3°		16.1	
MOON	SLRV Phase I AC-DRL (RCA)	"	716	500	500	—	0.9	1.0	*5.1 x 10^5	*64	*3.08 x 10^6	.015-34	22 to 2200	5%	5%	—	—	—	5 x 5 Dots	No	f/4	45°	11.6	5.75	
MOON	SLRV Proposal AC-DRL (RCA)	"	716	500	500	—	1.58	3.72	*5.1 x 10^5	*64	*3.08 x 10^6	.015-34	22 to 2200	5%	1%	—	—	—	5 x 5 Dots	No	f/3.5	42°	4.8	4.1	47
MOON	Orbiter 1, 2, 3	70mm film Photoscan	18,942 /strip	—	—	1/25, 1/50 1/100	20 Min	—	*9.6 x 10^8	*64	*5.75 x 10^9	—	—	—					Yes	No	f/5.6			145 Incl. Proc	26x22 x32
MOON	Apollo (Surface)	1" Secon	320				0.10	0.10	*1 x 10^5	*64	*6.1 x 10^5		.007-12,600		2%							70°	6.5	7.25	160
MOON	" "	1" Secon	1280		500		0.625	0.625	*1.6 x 10^6	*64	*9.8 x 10^6		"		2%							70°	6.5	7.25	160
MOON	Apollo (Command)	1" Vidicon	320	220	220	—	0.1	0.1	*1 x 10^5	*64	*6.1 x 10^5	0.1 -30									f/1.9 f/2.5	80°	5.8	4.5	84
MOON	Facsimile (Aeronutronics)	Scanner	500	0.10 -0.01°	0.1°		60 for 360°			*64			25-2200		0.2%	1%					f/7	50° x 360°	<10	10	49
MARS	Mariner IV	Vidicon	200 x 200	140	140	0.20	24	48	4 x 10^4	64	2.5 x 10^5								Yes	Yes	f/8	32 Min of arc		Head 3.5	
MARS	Voyager 1973 (Entry)	"	200 x 200	140	140					64	2.5 x 10^5												20	14	700
MARS	Voyager 1973 (Capsule)																						25	15	1500
MARS	Surveyor Study (Hughes)	1" Vidicon	600 200	700 200	700 200				3.6 x 10^5 4 x 10^4	64 64	2.16 x 10^6 2.4 x 10^5		To 5000		6% 6%	1% 1%			5 x 5	3 Color				16.1	
MARS	Orbiter Study (Boeing)	1" Vidicon	200x200 400x400	140 280	140 280	0.20 0.20	— 26	— 52	4 x 10^4 1.6 x 10^5	64 64	2.4 x 10^5 9.6 x 10^5												10.5	13.5	
MARS	Orbiter Study (JPL)	70 x 25mm Film	2100 x 750			.170	—	—	1.6 x 10^6	64	10^7	—	280								f/4.5	24°			

* Digital Equivalent

Figure 4-12 Image Sensors

Kortman[13] has classified data compression techniques under parameter extraction, redundancy reduction (e.g., of picture elements) and statistical encoding (e.g., of grey levels).

a. Preselection. It is obvious that selection of video quality, field angle and selection of which pictures are to be transmitted is an effective way to maximize information flow and minimize transmission requirements. At present this is done by earth command or by preprogramming picture sequences. For remote vehicle control, automatic decision-making logic could be incorporated into the vehicle.

First, the number of picture elements or grey levels could be varied. From some minimum number of picture elements, for vehicle control, an increase is indicated when objects of interest subtend less than, say, 16 picture elements. An increase in the number of grey levels is indicated when undesired contouring due to grey-level quantizing appears on large objects.

Second, the field angle can be varied. One typical criterion would be that, for straight-line vehicle motion, a smaller field angle is required to encompass the future path than for a curved vehicle path.

Third, video should be transmitted only when warranted by terrain characteristics/or mission needs. For example, on relatively smooth surfaces, as established by non-imaging sensors, the vehicle might be caused to progress without transmitting video data.

b. Preprocessing. One type of video processing prior to transmission which is within the state of the art is formation of composite images from various sensor data. For example, the output of an optical rangefinder could be synchronized to appear at the corresponding location on a video image. This would permit a low-quality picture to be transmitted instead of high-quality stereo pairs for measurements beyond a few feet.

A second type of prepocessing involves pattern recognition and decision making on the vehicle. Although this is not yet practical, intensive investigations by many groups (such as those at AC-DRL, MIT, RCA, and elsewhere) show promise for this approach.

A third type involves analog preprocessing to reduce grey-level requirements without the addition of quantizing noise. One way of doing this is to reduce low-frequency response over each scan and to increase the gain so that high frequencies, which contain most of the visual information, are emphasized.

4.5.1.3 DATA COMPRESSION. Data compression techniques applicable to processing of video are reduction in redundancy of picture elements and reduction of grey-level requirements by encoding. These and other approaches are the subject of intensive investigation by many groups. Table 4-X is a brief tabulation of typical study results.

All of the experimental results were reported to have been done by simulation where communication link problems were not experimentally investigated.

Element compression ratio (ECR) is defined by Kortman[13] as "the ratio of the number of data values presented at the input to the number of significant data values delivered to the buffer memory during a specific time value." He defines bandwidth compression ratio (BWCR) as "the ratio of the number of bits presented at the input to the number of bits delivered at the output of the data compressor. This ratio includes all penalties for identification, timing and synchronization and is therefore a true measure of overall compression efficiency."

It is possible, from this and other reports, to draw preliminary conclusions concerning the future usefulness of data compression for remote vehicle control.

1. Data compression may provide bandwidth compression ratios varying from 2 to perhaps 5 or 10. This is dependent on the nature of the subject, signal-to-noise ratio and required picture quality.
2. Data compression is accomplished at the cost of added equipment and complexity on the vehicle as well as at the receiving end.
3. Redundancy reduction techniques give poor results at signal-to-noise ratios much below 30 dB.

4.5.1.4 DISPLAYS. The field of information display has been approaching the level of a formal science in recent years. As a result, a great deal of information is now available both with regard to available hardware and the human factors involved in using hardware. However, for remote vehicle control, the real problem is to establish the nature of required displays and to see that input information is suitable.

TABLE 4-X
DATA COMPRESSION STUDIES

Picture Subject	S/N db	Compression Technique	ECR	BWCR	Subjective Quality	Predicted Future BWCR	Author
RETMA Chart	30	Redundancy Reduction	11.5	5.8*	Poor		Malling, L.R., SPIE Journal. Oct/Nov, 1960
RETMA Chart	20		3.4	1.7*	–		
Moon Crater	30		6.2	3.1*	Poor		
Moon Crater	–		51.0	25 *	Fair for Control		
Tiros Video	High	Redundancy Reduction	–	≈ 4	Fair for Control		Kortman, C.M., Proceedings of the IEEE, March, 1967
Gemini Video	Very High		–	≈ 6	Excellent		
Ranger Video	High		–	≈ 5	Excellent	> 6/1	
Tiros Video		Redundancy Reduction	–	4	Excellent	2 to 4 for Commercial TV	Hochman, D., et al., Proceedings of the IEEE, March, 1967
Aerial Photo			–	4.8	Excellent		
Missile Photo			15	7.5*	Excellent		
Portrait		Redundancy Reduction	3	1.5*	Excellent		Robinson, A.H. and Cherry, C., Proceedings of the IEEE, March, 1967
Scene			3	1.5*	Excellent		
Portrait		Encoding	–	1.5	Good		Golding, L.S. and Schulttheiss, P.M., Proc. IEEE, March, 1967
Cameraman	40	Encoding	–	1.5	Fair		Huang, T.S., et al., Proceedings of the IEEE, March, 1967
Cameraman	40		–	3.0	Usable		
Cameraman	40		–	2.0	Fair		
Cameraman	40		–	2.0	Fair		
Cameraman		Encoding	13.6	6.8*	Poor		Graham, D.N., Proceedings of the IEEE, March, 1967
Cameraman			16.0	8.0*	Poor		
Test Pattern			6.75	3.4*	Poor		
Crowd			3.8	1.9*	Good		
Portrait			22.7	11.3*	Fair		
Bus		Encoding	–	≈ 3	Excellent		Limb, J.O., Proceedings IEEE, March, 1967
Portrait			–	≈ 3	Excellent		
Portrait	High	Encoding	–	5	Poor		Huang, T.S., IEEE Spectrum, Dec 1965
Portrait	High		–	5	Poor		
Portrait	Low		–	5	Fair, noisy		
Portrait	High		–	15	Fair		
Portrait		Encoding	–	2	Good		Bisignani, W.T., et al., Space and Aeronautics, June, 1966
Lunar Crater			–	2	Good		

* Assuming BWCR 1/2 ECR

For example, a display may show direct video plus engineering information. Or it may be a totally synthetic display of information generated on the earth or in space. Or it may be a display for monitoring a completely automatic vehicle.

An operator may require rapid display of stereo pictures or of measured information from stereo where picture data are of such quality that automatic rapid processing and display is not possible.

Therefore definition of suitable displays for remote vehicle control must be made later in this study when specific ranges of system parameters are established.

4.5.2 Telecommunications

With respect to telecommunications, the major decisions are related to the desirability of preprocessing data, and whether the link should be direct or indirect. If indirect, shall the relay be located on the surface or in orbit, and if in orbit, shall it be synchronous with the planet's rotation or nonsynchronous, inclined or equatorial? Within the frame of reference of the RVMC problem, telecommunications capacity will have the major impact on the decision-capability requirements of the vehicle. The Rover control problem might be stated as follows:

- to detect and evaluate hazards and make judgments on the capability of the vehicle to drive through, around or over them
- to find acceptable paths through which the vehicle can safely pass

with the artificial vision, restricted view and delayed responses that characterize the control system.

Uncertainty about terrain conditions creates the greatest concern about vehicle safety. For the first developmental Rovers, this uncertainty may vary inversely with telecommunication channel information capacity. Therefore, the large difference in information rates between lunar and Martian missions will have a major impact on Rover control system requirements and control techniques and upon vehicle performance for each application. In either application there must be a balance between the input instructions of the programmer and the outcome of the machine. The achievable Rover-to-Earth bit rate will determine the required machine self-organization as it interacts with the environment of the survey body.

Fundamentally, the ability of a deep space communication system to track, command, or acquire telemetered data from a vehicle is a function of the ratio of signal level to noise level. Signal level varies inversely with the square of the distance of transmission. Design of a system to communicate out to a particular distance takes the form of making up for space losses by transmitter power, antenna gains, and receiver sensitivity. Minimizing noise levels depends on many factors, including avoidance of RF noise sources and design of the receiver preamplifier.

Reference 14 forecasts Moon-to-Earth data rates ranging from 10^6 bits per second to more than 10^7 bits per second before 1970.

The Mars-Earth communication link presents a problem that is much more difficult than the Moon-Earth communication link because distance is three orders of magnitude greater and rotation rate relative to the earth sphere is two orders of magnitude greater. Rover antenna gains will be limited by vehicle dimensions and mobility characteristics. In addition, it may be difficult to achieve precise tracking because of limitations on the antenna drive mechanism size, weight, and complexity. Writers on the subject of the Mars-Earth communication link have used so many diverse assumptions that it is difficult to correlate these and to arrive at a conclusive estimate of feasible data rates for a roving vehicle. However, based on Reference 15 (which is a preliminary study of data rates from Mars for various antenna sizes), it appears that the bit rate from Mars will be two to four orders of magnitude lower than the bit rate from the moon.

4.5.3 Data Processing Equipment

It is evident that at planetary distances the telecommunications links, particularly the "down-link" from the survey planet to Earth, are in essence long, narrow pipelines which offer a significant impedance, in the operational sense, to remote vehicle control. This suggests that the general control system configuration for planetary exploration will probably be as in Figure 4-13. The character of the long-time-delay, narrow-bandwidth, transmission channels at planetary distances tends to isolate the SFOF components from the vehicle components, and increases the value of "local feedback" at both the earth and survey planet terminals of the DSIF links.

"Local feedback" on the vehicle consists of data storage, logic, and self-guidance capabilities. With these capabilities fewer and more complex commands can be given to

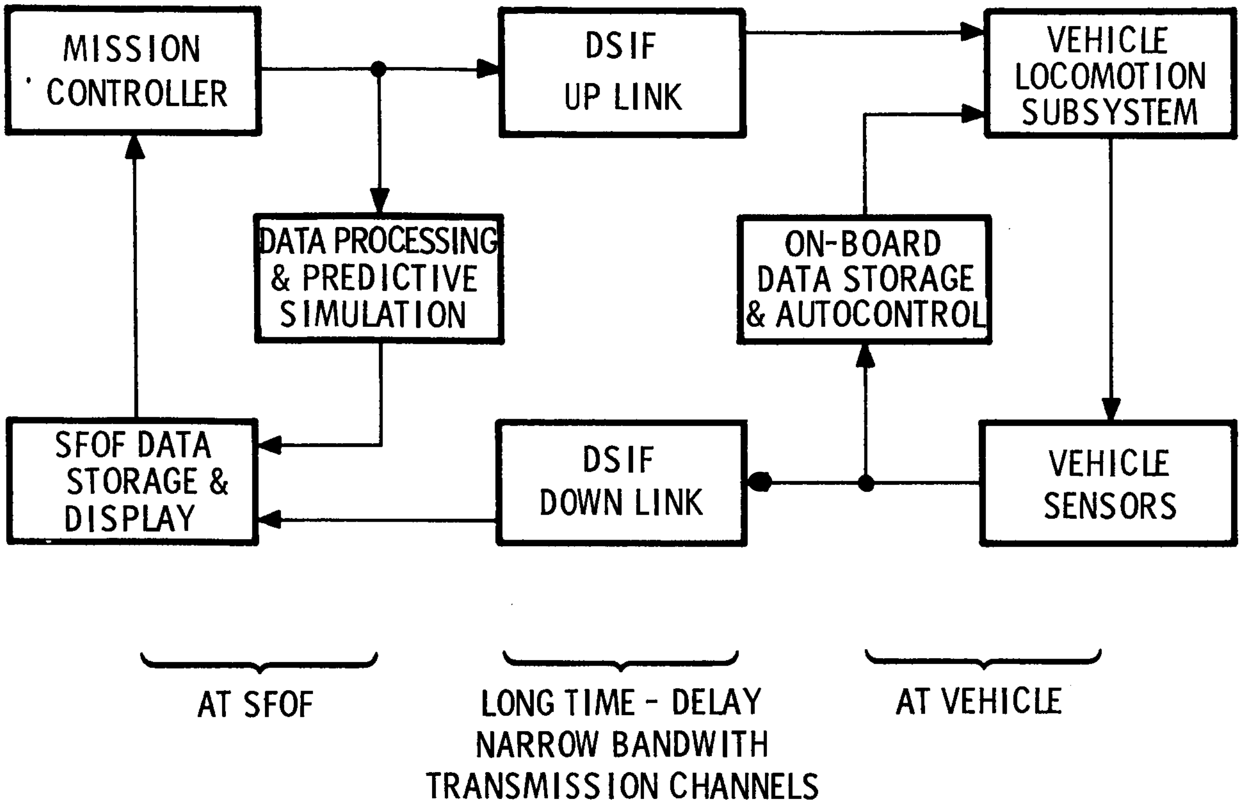

Figure 4-13 General Control System Configuration for Planetary Exploration

the vehicle, the vehicle can make longer and more circuitous locomotion operations between commands, and the vehicle may have an adaptive capability to adjust to locomotion factors such as wheel slip and terrain reaction forces, and locally variable terrain conditions.

By such a system configuration as shown in Figure 4-13, the vehicle is endowed with a capability for short-term self-control by virtue of on-board storage of command sequences, decision logic, and image data. A lengthy and perhaps complex sequence of commands could be transmitted to the vehicle which would then proceed to execute the commands without further control from the earth. After completion of the sequence, which would include the gathering and storage of additional sensor data, the vehicle would stop and transmit its stored data to the earth.

4.5.3.1 DATA STORAGE AND LOGIC EQUIPMENT STATE-OF-THE-ART. Indicative of the present state of the art for data storage and logic equipment is the Apollo guidance computer (Reference 16). This computer system consists of memories, an adder, instruction decoder, memory address decoder, and seven adressable registers. The computer can execute 40,000 instructions per second. Table 4-XI lists the Apollo computer characteristics.

Instructions can address registers in either the fixed or the erasable memory. Each memory word has 15 information bits and a parity bit. Data are stored as 14-bit words with a sign; instruction words have three order-code bits and 12 address-code bits. The normal sequence of instructions can be broken by a number of involuntary sequences, which are not under normal program control. These are triggered either by external events — an astronaut's entering data from the keyboard, for instance — or by certain overflows within the computer.

Computer words flow over prelaunch and inflight radio links between the computer and ground control. The downlink rate is 50 words or 800 bits per second. During one memory cycle the interface stores a full 16-bit word in a flip-flop register; upon command, it sends the bits serially in a burst to the communications system of the spacecraft. Each bit received on the uplink requires a memory cycle; the maximum rate is 160 bits per second.

Table 4-XI
COMPUTER CHARACTERISTICS FOR APOLLO GUIDANCE

Word transfers	Parallel
Word length	16 bits = 15 data + 1 parity
Number system	Modified one's complement
Memory cycle time	11.7 μsec
Fixed memory	36,864 words
Erasable memory	2,048 words
Normal instructions	34
Involuntary instructions (interrupt, increment, etc.)	10
Interrupt options	10
Addition time	23.4 μsec
Multiplication time: 14x14 bits	46.8 μsec
Double-precision addition time	35.1 μsec
Increment time	11.7 μsec
Number of counters	29
Power consumption	Less than 100 watts (including two DSKY's)
Weight	58 pounds (computer only)
Size	1.0 cubic foot (computer only)

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4.5.3.2 FUTURE TRENDS IN DATA STORAGE. Each of the Apollo computer memory's six modules stores 98,304 bits of information. The core rope memory has a bit density of approximately 2,000 bits per cubic inch, including all driving and sensing circuits, interconnections, and packaging hardware.

The results of an RCA survey[17] of advanced storage techniques have been tabulated in Table 4-XII. Storage densities of 3,000–6,000 bits per cubic inch, including the same functional hardware as for the Apollo core rope memory, may be achievable in three to five years.

Table 4-XII
SURVEY OF ADVANCED STORAGE TECHNIQUES (REFERENCE 17)

Type	Adequate for Video Storage	Power Consumption	Storage Density (Bits/in.^{3}) (Excluding Electronics)	Volume For 2×10^6 Bits (cu. in.) (Excluding Electronics)	Volume Electronics For 2×10^6 Bits (in.^{3})	Total Weight For 2×10^6 Bits (lb)
Ferrite Memories						
a) Toroid	Yes	Low	2,000	1,000	500	50
b) Bead	Yes	Low	8,000	250	500	
c) Apertured Plate	Yes	Low	10,000	250	500	
d) Laminated Sheet	Yes	Low	20,000	200	500	
e) Film	No					
f) Flute	Yes	High Peak	8,000	250	500	
g) Waffle-Iron	Yes	High Peak	10,000	250	500	
Magnetic Metal Memories						
a) Twister	No					
b) Thinfilm	Yes	Low	50,000 – 500,000			
c) Permalloy Transfluxer	Yes	Low				
Cryogenic Memories						
a) Wire-Wound Cryotron	No					
b) Thin Film Cryotron	No	High				
c) Cryosar	Yes					

4.5.4 Power Systems

Since power requirements necessarily consume a part of the vehicle gross weight, a brief discussion of power systems is in order. An electric power source is required by the roving vehicle to energize the propulsion and steering motors, the scientific instruments, the data processing and control equipment, and the telecommunications equipment. The atmospheres of the moon and Mars limit the possible choices of power sources to nuclear reactor, radioisotope, solar panel, fuel cell, and battery systems. The relatively low power requirements of the vehicles to be considered in this study eliminate any consideration of reactor power systems. The desire to define a roving vehicle which is not range-limited, and with operating lifetimes of from months to years, tends to eliminate fuel cells from practical consideration. Likely candidate power systems are:

(1) radioisotope-thermoelectric generator + high energy density (15—20 watt-hours/pound) batteries

(2) solar panels + low energy density (2—3 watt-hours/pound) batteries.

The nickel-cadmium cell is the only proven reliable battery system for long-term service where rapid recharge is needed. For the Martian case, this battery would probably be used whenever a solar-panel power system is used, because of its ability to survive deep discharges. If an operating life of several years is necessary, an energy density of 2 watt-hours per pound can be assumed for the nickel-cadmium cell.[18]

The silver-zinc battery has a relatively short cycle lift but, for the lunar case, studies might indicate the existence of workable silver-zinc/solar-panel combinations.

A radioisotope-thermoelectric generator (RTG) power system operates continuously and requires batteries to supply only peaking power. Therefore, the silver-zinc cell can be considered appropriate for this power source and can produce 15 to 25 watt-hours per pound, depending upon the depth of discharge.

At present, RTG's produce about 1.2 watts per pound. A capability of three watts per pound within the next five years has been predicted.[19] For cooling purposes, a 2π steradian field of view is required for thermoelectric generators. An RTG produces nuclear radiation and magnetic fields which may interact with other Rover subsystems. These fields can lead to the compromise of some of the scientific experiments or can cause radiation damage of electronic components during a long-duration mission.

Solar-cell power systems are being used on 30 or 40 different spacecraft; the range of power outputs is from 15 to 500 watts. Conclusions reached by RCA[20] in designing an energy source for the SLRV are as follows:

- RTG's are competitive with orientable solar arrays in the approximate range of 1.5 to 2.0 watts per pound of converted power for operating times greater than six to ten hours
- The orientable solar array has limited growth capability compared to an RTG.

In addition, solar panels may suffer performance degradation from meteorite damage and dust or from atmospheric conditions, and they require mechanisms for orientation. Their area may present structural problems in the high winds that may exist on Mars. It would appear that, if present predictions of RTG performance are realized, this would be the preferred approach to powering unmanned roving vehicles on Mars, and probably also lunar vehicles.

4.5.5 Mobility

The mobility subsystem of the roving vehicle must be considered as an element of the motion control system in the sense that, as weight is allocated to greater mobility (especially as measured in terms of hazard negotiation), requirements placed on the system for detecting and measuring hazards may be relaxed. There is thus a weight tradeoff possible between basic mobility and the complexity and weight that must be incorporated in the control function.

4.5.5.1 PERFORMANCE VARIABLES. Vehicle capability may be described in terms of several variables, the most significant of which are:

1) Obstacle Capability
    a) Step height
    b) Crevice width
2) Maneuverability
    a) Turning radius
    b) Off-tracking or encroachment
3) Stability
    a) Static
    b) Dynamic

4) Gradeability
5) Locomotion energy
6) Payload-to-gross-weight ratio.

Obstacle capability, maneuverability and stability depend mainly on the geometry of the mobility subsystem, while gradeability (or ratio of drawbar-pull to weight) and locomotion energy are most closely related to the overall size, but also depend to a great extent on the degree to which one is willing to compromise overall mobility performance.

Many other factors ultimately affect the mobility performance of a vehicle in adverse terrain. Perhaps one of the most significant is the capability to avoid impediments which would normally be negotiable, but which could cause termination of the mission if encountered in certain ways or in certain combinations. For example, small rocks can jam wheels, or outcroppings can become entangled in structural members. Although this type of mobility performance may be crucial to mission success, it is difficult to evaluate quantitatively. It results mainly from careful attention to such considerations in the design process.

Attempts have been made in the past to derive a point-valued measure of the mobility performance of vehicles — a mobility "index" or "figure of merit" — which subsumes all of the important performance parameters under one number. Such attempts have not generally been very satisfying because they usually involve the a priori assignment of normalizing functions and weighting factors. The results are often sensitive to the arbitrary choices of weightings and normalizations, and are useful only when related to specific missions for which these priority assumptions hold. For this reason, no such index of performance is used in this study. In the RVMC study the interest is in a broad spectrum of vehicles to perform a variety of missions in a variety of environments. When the importance of specific performance parameters to the control function is better understood, it might be possible to derive a "control index of mobility performance," but such a figure would probably be of doubtful value.

4.5.5.2 VEHICLE SURVEY. In order to provide a basis for trading off the weight and performance of mobility subsystems against the weight and performance of other components of the RVMC system, a survey was made of vehicles which have resulted from a reasonably thorough preliminary design effort at AC-DRL. All of these vehicles were designed for specific missions and delivery systems and all are intended for lunar operation. The designs reflect, to some extent, features which are peculiar to those missions and delivery systems and the comparison therefore is not strictly on a common basis. Nevertheless, they comprise a useful basis for characterizing the performance, weight, and size relationships of roving vehicles for purposes of the RVMC study. Because of the relatively greater accessibility of good data on vehicles having six wheels, this is the type used for all data points in this survey.

Four such vehicles have been used to characterize a broad spectrum of gross weights ranging from 100 pounds to 24,000 pounds. The largest vehicle was not carried through a preliminary design, but has been included to show the trends beyond the range of vehicles that have been through a preliminary design.

4.5.5.3 VEHICLE DESIGN DATA. Table 4-XIII shows the important design data for the four base vehicles of the survey. The dimensional relationships are plotted in Figure 4-14. Overall length has arbitrarily been chosen as the common independent variable. It is seen that all dimensions scale approximately proportionately, except tread and overall width. In the absence of form factor constraints, one would expect geometric similarity. The lack of proportionate scaling for width and tread among these vehicles does, in fact, arise from the envelope constraints which were imposed. In the absence of such constraints, an overall width-to-length ratio of about 40—60 percent is a reasonable compromise, as shown by the dashed lines in Figure 4-14.

Table 4-XIII
VEHICLE DESIGN DATA

Vehicle Description	O/A Size (in.)		Wheel Size (in.)		Wheel Base (in.)		Tread (in.)	Gross Weight (lb)	Mobility Weight (lb)	Payload Weight (lb)
	Length	Width	Dia.	Width	Front	Rear				
SLRV Phase I	72	30	18	6	27	27	24	85.1	26.4	58.7
Specified LSSM	160	92	40	10	58	62	82	2,000	590	1,410
MOLAB	242	125	60	15	87	95	110	7,166	1,240	5,926
AC-DRL Saturn V Concept	576	204	144	30	216	216	174	24,000	8,300	15,700

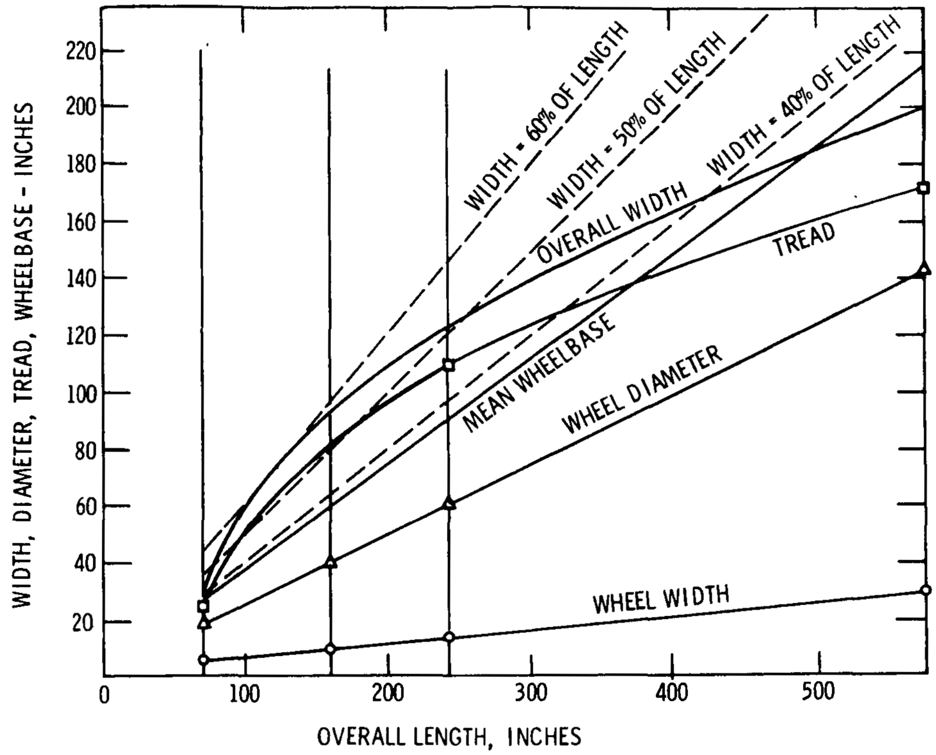

Figure 4-14 Dimensional Relationships of 6 x 6 Lunar Vehicles

Under the assumption of geometric similarity, only one characteristic dimension is needed to describe the size of a vehicle. Figure 4-15 shows the manner in which gross vehicle weight varies with the overall length, overall width, and with the product of length by width for the four vehicles considered. Least-square linear fits in each of the three cases yield relationships of the form

$$\text{Weight} = K\, X^B$$

where X is the independent variable (length, width, or length-by-width product).

Of the three cases, the relationship between gross weight and width shows the least variance and follows a cube law as follows:

$$\text{Gross weight} = 3.33 \times 10^{-3}\, (\text{width})^3$$

where weight is in pounds and width is in inches.

This relationship cannot, of course, be adopted as completely general, since the weight is obviously not independent of overall length. For vehicles where the width is between 40 and 60 percent of the length, though, it is probably useful for preliminary estimates.

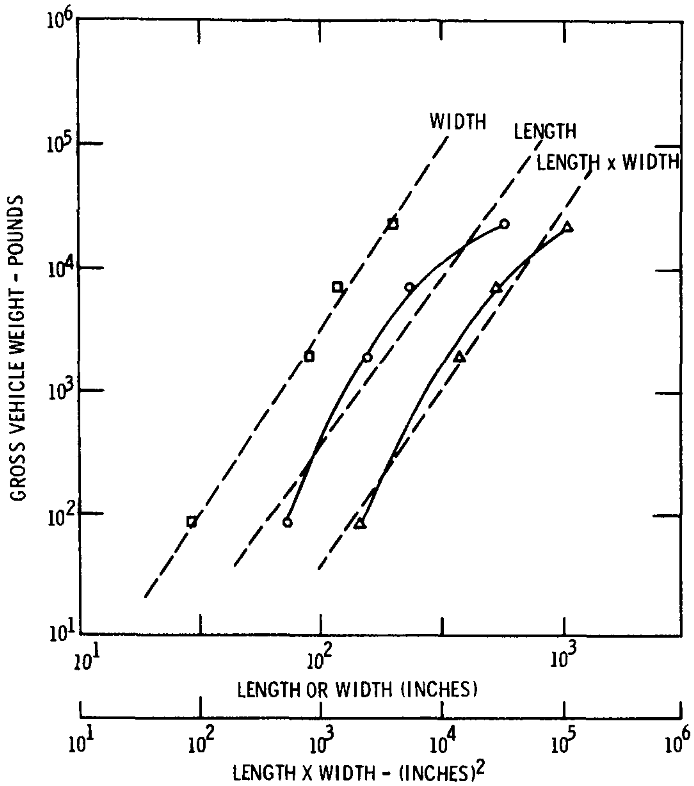

Figure 4-15 Relationship between Weight and Size

From the data in Table 4-XIII, the relationships between gross weight, mobility subsystem weight, and payload weight may be noted. Here it is assumed that the mobility subsystem weight consists of the following components: chassis-frame, wheels, wheel drives, steering, axles, structures and/or compartments to which payload items are attached, and fenders and suspension components, when used. No weight is included for power or energy associated with locomotion, since this is quite mission-sensitive.

For the four vehicles, the gross weight breaks down into payload and mobility as shown in Table 4-XIV. One sees that for lunar vehicles the mobility subsystem constitutes about 30 percent of the gross weight. The apparently anomalous situation in the case of the MOLAB arises from two main considerations:

(1) The MOLAB provided an enclosed "shirtsleeve" working environment in a cylindrical shell. This shell provided some of the structural functions normally performed by the chassis, yet its weight was charged to crew systems.

(2) MOLAB wheel drive weights were based on an early design and early performance requirements. Subsequent experience with the design and increased performance requirements caused increases in the weight of later designs of wheel drives of this type.

As explained below, the 30% of gross weight allocable to mobility in lunar vehicles must be increased for Martian applications.

Table 4-XIV
BREAKDOWN OF GROSS WEIGHT

Gross Weight, lb	Payload %	Mobility, %
85.1	69.0	31.0
2,000	70.5	29.5
7,166	82.7	17.3
24,000	65.4	34.6
Average	71.9	28.1

4.5.5.4 VEHICLE PERFORMANCE DATA. Table 4-XV shows the performance characteristics of the three vehicles which have been thoroughly analyzed. Those performance characteristics which are primarily dependent upon geometry are plotted in Figure 4-16. The step and crevice performance is affected by the placement of payload components, both from the standpoint of geometrical interference and from the standpoint of uniform load distribution among the wheels. In Figure 4-16, minimum turning radius has been inverted and plotted as maximum curvature (1/R) and off-tracking has been plotted on a reversed scale. This emphasizes the desirability of making the maneuverability parameters small and illustrates the inherent tradeoff between obstacle capability and maneuverability.

To a first approximation, obstacle capability is proportional to size and maximum path curvature is inversely proportional to size. Off-tracking depends on both size and steering geometry. Since the three vehicles used in the plot of Figure 4-16 have different steering geometries, the curve for off-tracking should be used merely as a rough guide.

Table 4-XV
PERFORMANCE CHARACTERISTICS OF VEHICLES

Vehicle Description	O/A Length (in.)	Gross Weight (lb)	Obstacles (in.)		Maneuverability (in.)		Gradeability* (DP/W)			
			Step	Crevice	Min. Turn.	Off Track	k_ϕ=.05 to .08	.5	3.0	6.0
SLRV Phase I	72	85.1	30	20	68	6	.167	—	—	—
Specified LSSM	160	2,000	45	49	227	9	.166	.53	.56	.58
MOLAB	242	7,166	76.5	76.5	282	14	.193	.537	.568	.585

* DP/W in terms of lunar weight

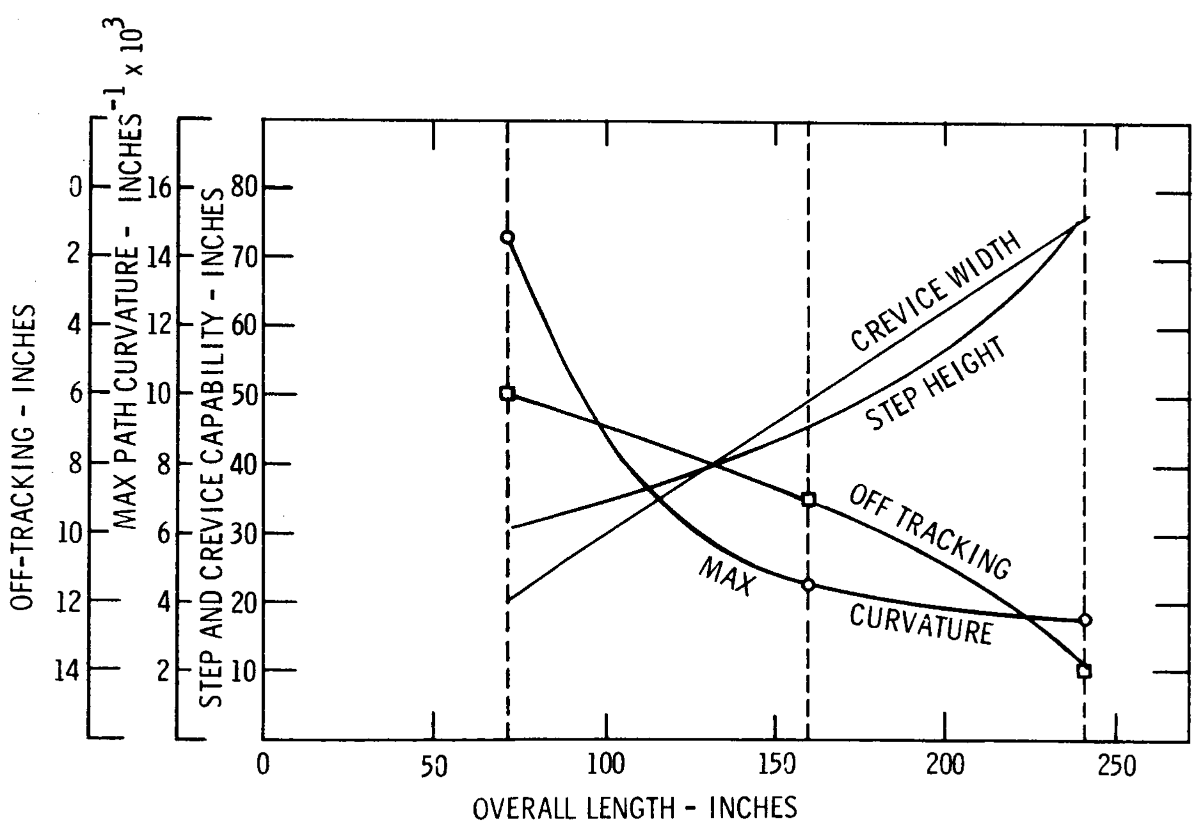

Figure 4-16 Obstacle Capability and Maneuverability

Gradeability is expressed in terms of the ratio of drawbar-pull to weight, where the weight in this case is the gross weight of the vehicle on the moon. This is the sine of the angle of grade negotiable by the vehicle, and is primarily dependent upon the weight and the soil properties. Soil values used for the three vehicles were not the same in all cases. The SLRV calculations are based on a JPL soil model having the properties $k\phi = 0.083$, $\phi = 20^{\circ}$, and $n = 1.0$, resulting in a slightly lower relative value for DP/W. Allowing for this slightly lowered value, the relationship appears roughly linear, but is at any rate largely independent of gross weight. There is, however, an apparent strong dependence upon soil properties.

The calculation of locomotion energy requirements has generally been based on the Bekker equations[21] used with a specified soil-slope model, supplemented by assumptions of the person making the calculations. Since the three vehicles considered have been evaluated with respect to vastly different assumptions and terrain models, no good comparison can be made. It can be shown, however, that locomotion energy for a given terrain and a specified set of assumptions is roughly proportional to the weight in situ. For the LSSM, having a lunar weight of 2000/6 = 333 lb, the energy required for level terrain having $k = 0.5$ is about 120 watt-hr/km. Grade requirements for a given terrain model add to this. One is led, then, to this approximate relationship for moderate soils:

$$E = 0.36\ w + \text{Grade energy}$$

where E is energy in watt-hr/km, and w is weight in situ. For harder soils energy will be less and for softer soils it will be greater.

Most of the data given above are based on vehicles designed for the lunar environment. Since the Martian gravity is about 2-1/4 times that of the moon, certain weight-dependent values will be different for Mars. A cursory study of this effect indicates, for example, that mobility elements of Martian vehicles will constitute about 40 percent of the gross weight rather than the 30 percent cited above for lunar vehicles.

Drawbar-pull-to-weight ratio will remain about the same, but locomotion energy for a vehicle of comparable size and earth weight will increase by a factor of about 2-1/4. This will require either an increase in power and less weight available for science, control, and communication, or a decrease in speed, or both.

5. SUMMARY AND IMPLICATIONS

During the first quarter, work on the Roving Vehicle Motion Control Study has established the foundations and the framework upon which the later configuration and analysis of motion control systems will be structured for both the lunar and planetary cases. The problem has been viewed as one of systems analysis where many elements work together in such a manner as to achieve a specified objective under externally imposed conditions or constraints. In this case, the objective is to move a payload about the surface of a remote heavenly body, both safely and efficiently, in order to maximize the scientific data return of an unmanned soft-landed mission. The control system constraints, especially in the case of Mars, are severe, and they indicate the need for very careful tradeoff analysis to insure an optimal balance between all elements. They also indicate a need for a relatively high degree of automation.

Past studies have found that, even at lunar distances, the 1.3 second one-way time lag associated with communication often makes continuous motion of a roving vehicle very difficult (except at very low speeds and in very simple terrain). The conclusion has been that a step-by-step mode is preferable where a vehicle steps forward a specified distance, stops, and on command sends one or more pictures back to the controller. After evaluation of the pictures, the controller issues a new command, and the cycle repeats. Thus, each command is followed by confirmation that the command was successfully carried out before a new command is issued.

The distance to Mars and the associated time delays (3 to 22 minutes one-way) make this approach unsuitable as a normal mode of operation. Even if communication with the earth-based control center could be carried on continuously, the time needed to carry out even the simplest useful missions would become unacceptably long and could be almost totally dominated by the transmission lag. Aggravating this situation is the rotation of Mars, which may limit communication operation times to a few hours per day, and the power/bandwidth tradeoff situation, which reduces practical information rates to a few kilobits per second, at best. The realization of even this low a rate requires a high-gain antenna which in turn requires significant periods of time to orient toward the earth.

This then leads to the operational concept wherein a lengthy sequence of commands is transmitted and stored, to be carried out automatically, and normally without further contact with the earth until the completion of the command sequence. Since it appears that sensors are unlikely to yield sufficient information to allow the detailed definite judgments required for such a command sequence, on-board logic would have to be provided to override and modify the command sequence in case unforeseen hazards are encountered. It might thus seem reasonable to consider also a system capable of formulating its own commands consistent with the attainment of more general objectives specified from earth. The next logical step would be to include adaptive and/or learning capability so that the on-board decision processes would be modified by the immediate environment and by its past experiences.

There thus seems to be a fruitful area for future investigation crystallizing out of the initial stages of this study. Although no effort in the first quarter was devoted to adaptive or learning system philosophies, the desirability of directing future effort along these lines was clearly demonstrated.

Several other important areas were not touched upon or were incompletely handled during the first quarter. The most significant of these is the area of navigational techniques which, while not explicitly stated in the work plan, are so closely related to the control problem that they must be given some consideration in the overall study. Another is the area of personnel usage and capability, which may pose radically different problems for the lunar and planetary cases in light of the above discussion.

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